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Characterization of orography-influenced riming and secondary ice production and their effects on precipitation rates using radar polarimetry and Doppler spectra (CORSIPP)

Project Description

1 Starting Point

1.1 State of the art and preliminary work

Precipitation is a major component of the climate system connecting the atmosphere to the hydrosphere. A comprehensive understanding of the precipitation formation processes is required to understand how the water budget is changing in a warming climate. In mid-latitudes, most precipitation is generated through the ice phase in mixed-phase clouds (Mülmenstädt et al., 2015), but the exact pathways through which ice, liquid water, cloud dynamics, and aerosol particles are interacting during ice, snow[1], and rain formation are not well understood (Shupe et al., 2008; Stewart et al., 2015). The frequency of occurrence (FoO) of precipitation formation pathways such as riming and aggregation is also not well characterized (Morrison et al., 2020). In the temperature range between $-10\,^\circ$C and $0\,^\circ$C, the number of active ice nucleating particles (INP) is very low (DeMott et al., 2010), but measured ice crystal concentrations are often orders of magnitude larger than what would be expected from primary ice production only (Korolev and Leisner, 2020) indicating that other ice formation processes such as secondary ice production (SIP) are occurring. While it is recognized that SIP is a fundamental cloud microphysical process explaining this gap, it is unclear both qualitatively and quantitatively which cloud processes contribute to SIP (Field et al., 2017[2]; Korolev and Leisner, 2020). Due to their high impact on ice particle number concentration and mass, SIP and riming, respectively, are likely related to the largest uncertainties with respect to quantitative snowfall formation.

Filling the gaps in our understanding of SIP and riming is especially crucial for mountainous regions that are particularly vulnerable to changes in precipitation and the water budget such as the ratio between rain and snowfall. This is because the mountainous water budget is driven by the storage of water in the snow pack, and rain can lead to increased runoff and erosion (Hart and Loomis, 1982). In addition, cloud dynamics and precipitation formation are more complex than over flat terrain due to interactions with orographic effects. As a direct consequence of the limited precipitation formation process understanding, atmospheric models cannot properly simulate precipitation in mountainous regions. This results in challenges when quantifying the mountainous water budget and how it is changing in a warming climate (Huss et al., 2017).

For riming, significant uncertainties exist with respect to the collection efficiencies of ice particles due to their complex shape. The qualitative importance of riming for the snowfall amount is unclear. While it has been found that rimed particles contribute 30-63% to the total snow mass (Harimaya and Sato, 1989; Mitchell et al., 1990), Kneifel and Moisseev (2020) estimated that riming occurs only in 1-8 % of the non-convective ice containing clouds and showed a strong increase with increasing temperatures between $-12\,^\circ$C and $0\,^\circ$C. Yuter and Houze Jr (2003) found that riming and other ice processes are particular important for orographic precipitation formation. While it is commonly assumed that significant liquid amounts are required for riming in mixed-phase clouds, Fitch and Garrett (2020) found rimed particles at liquid water paths as low as 50 $\mathrm{g\,m^{-2}}$. Riming is an important microphysical growth

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[1] The separation between snow and ice is somewhat arbitrary (see discussion in Schmitt and Heymsfield, 2014), but we refer to precipitation at the ground as snow, and to crystals aloft as ice.

[2] Underlined references indicate publications with the proposers as (co-)authors or supervisors of theses

process in cold clouds, which plays a significant role in precipitation formation while at the same time posing a severe weather hazard by aircraft icing (Cao et al., 2018; Serke et al., 2010). There is also an ongoing need to better represent riming in numerical weather prediction models (NWP, Morrison et al., 2020).

Also for SIP, the exact role for quantitative snowfall formation is unclear. A recent observational study by Luke et al. (2021) found that the frequency of SIP was only $<$10% over the multi-year study period even though the processes assumed to be required for SIP—riming and supercooled drizzle formation—occur much more frequently. However, when SIP did occur, it lead to an up to 1000-fold increase in ice number concentration, highlighting the importance of understanding the role of SIP for the precipitation flux from clouds to the surface. Numerous SIP processes have been proposed and studied in the literature (Field et al., 2017; Korolev and Leisner, 2020). For the two SIP processes most commonly studied—rime splintering (Hallett and Mossop, 1974) and droplet freezing fragmentation (Koenig, 1965)— Luke et al. (2021) found that the latter process was found to be more efficient in terms of derived ice-multiplication factor, i.e., enhancement of ice particle number concentration (N_i). The FoO of SIP events between $-10\,^\circ$C and $0\,^\circ$C ranged between 1-10 % (depending on radar reflectivity thresholds applied) and peaked at about -5 °C which was attributed to the temperature region most favorable to the growth of ice needles and columns. These particles then cause the detected polarimetric signatures (i.e., increase in LDR) that the technique is based on. The results are in general agreement with Rangno and Hobbs (2001) who found evidence that the presence of supercooled drizzle droplets is often required for ice formation. Luke et al. (2021) showed a case study where updrafts lead to SIP through droplet freezing fragmentation which could indicate that the SIP frequency is different in complex terrain. Orographic waves such as Kelvin-Helmholtz waves or gravity waves are particularly favorable for droplet growth (Lohmann et al., 2016) so that they might be favorable for riming and SIP. Studies by Keinert et al. (2020) and Lauber et al. (2021) also state that orographically forced updrafts and high wind speeds or high turbulence values (as common in mountainous regions) are expected to increase the likelihood of SIP via droplet freezing fragmentation, which we will investigate. Contrarily, the rime splintering process is assumed to be rather slow so that in updraft conditions particles often leave the temperature zone favorable for rime splintering before a larger number of secondary ice can be formed (Hobbs and Rangno, 1990; Mason, 1996).

The lack of precipitation formation/SIP process understanding is related to the deficits of our observational capabilities (Morrison et al., 2020). In-situ observations are limited in their temporal and spatial coverage and may not be perfectly suited to (statistically) validate mechanisms proposed by laboratory and theoretical SIP studies. Ground-based remote sensing offers high spatio-temporal resolution of cloud and precipitation observations and provides the opportunity for statistical analysis (Bühl et al., 2017) even though the transformation from measurement into state space is non-trivial. Only recently, the climatological significance of riming and SIP has been assessed using long-term ground-based remote-sensing observations: Kneifel and Moisseev (2020) related radar mean Doppler velocity (MDV) to rime mass fraction using an extensive ground-based in-situ dataset. Luke et al. (2021) identified SIP from Doppler spectral reflectivity and spectral linear depolarisation ratio (LDR) based on a six-year vertically-pointing Ka-band cloud radar dataset of the US-Department of Energy (DoE) Atmospheric Radiation Measurement (ARM) site in Utqiagvik, Alaska. Specifically, increases of spectral LDR of the slow-falling particle-population to values corresponding to ice needles and columns (larger than -16 dB) concurrent with increases of spectral reflectivity above a threshold value were used to infer the occurrence of SIP. Based on exploiting the co- and crosspolar radar Doppler spectra, they accomplished an additional detection of supercooled drizzle drops and rimers (fast-falling ice particles). Both introduced techniques rely on absolute Doppler velocity measurements and can thus only be applied in non-convective conditions and/or flat terrain where the correlation between mean Doppler velocity (MDV) and riming holds true.

Strong up- and downdrafts in convective conditions or orographically induced waves in complex terrain can however shift the observed radar MDV by up to several m s^{-1}, so that MDV cannot be correlated with riming. Motivated by that, Vogl et al. (2021) developed a MDV-independent cloud radar-based riming identification method in SPP-PROM Phase I Project PICNICC where H. Kalesse-Los was Co-PI. This method capitalizes on the fact that strong riming creates fingerprints in the radar Doppler spectra and the derived moments (not only in the MDV). The combination of radar reflectivity, skewness and the width between left and right edge of the radar Doppler spectra above a noise threshold are used as input features to a set of artificial neural networks (ANNs). The predicted riming index is obtained independently from MDV, which is crucial at sites in complex terrain.

Recently, polarimetric cloud radars operating at higher frequencies (X-, Ka-, and W-band) have become more widely used to study hydrometeor shapes and microphysical growth processes in mixed-phase clouds (e.g., Kumjian et al., 2014; Myagkov et al., 2016b; Schrom and Kumjian, 2016; Matrosov et al., 2017; Kumjian et al., 2020; Pfitzenmaier et al., 2018; Vogel and Fabry, 2018; Matrosov et al., 2020). Compared to precipitation radars, these cloud radars operating at shorter wavelengths are more sensitive to smaller hydrometeors and thus allow for the characterization of hydrometeor shapes and microphysical processes toward the onset phase of precipitation. The series of mixed-phase cloud studies of Oue et al. (2015, 2016, 2018, 2021) based on complementary information of radar polarimetry and cloud radar Doppler spectra analysis found that riming and aggregation remain difficult to distinguish based on bulk reflectivity and bulk differential reflectivity gradients but also that some differentiation is possible based on MDV profiles. In that context, radars operating in simultaneous-transmission-simultaneous-reception (STSR- or hybrid-) mode are valuable tools since they measure a large set of polarimetric variables, which cannot be obtained by conventional cloud radars with single polarization or the LDR-mode. The polarimetric variables measured with STSR-mode radars are sensitive to hydrometeor properties such as size, shape, phase, density, and orientation. With respect to the dependency on number concentration, there are two groups of polarimetric variables: First, the backscatter polarimetric variables such as differential reflectivity Z_{DR}, correlation coefficient ρ_{HV}, and backscattering differential phase δ are immune to the particles number concentration. Second, differential attenuation A_{DP} and differential phase shift ϕ_{DP} as well as its range derivative specific differential phase K_{DP} characterize how the radar signal is transformed while propagating through a medium filled with scatterers which makes them proportional to the number concentration.

To use the polarimetric variables of STSR radars for quantitatively characterizing the shape and orientation of scatterers, Myagkov et al. (2016a) developed a polarimetric retrieval technique combining Z_{DR} and ρ_{HV} of elevation scans based on previous work by Matrosov (1991), Matrosov et al. (2012), and Melnikov and Straka (2013). The technique provides a polarizability ratio of ice particles (Fig. 1) which is a function of the aspect ratio and density of ice particles. For pristine ice crystals (relatively high density of 0.4–0.9 g cm^{-3}) the polarizability ratio and, in turn, polarimetric variables, are more sensitive to the aspect ratio. In contrast, for ice particles with low density (i.e., aggregates) the sensitivity to the aspect ratio is reduced (Fig. 1). Thus, the polarizability ratio is mainly valuable for the shape characterization of ice particles with high density. Therefore, so far, this method has been only applied to areas close to cloud tops, where the degree of aggregation/riming is expected to be low (Myagkov et al., 2016a) leaving the full

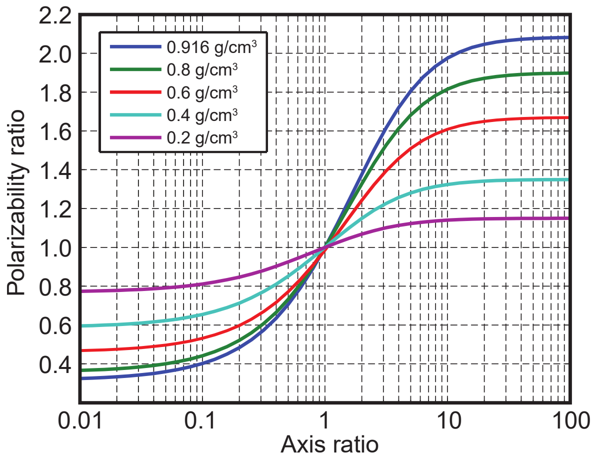

Figure 1: *Polarizability ratio as function of axis ratio and ice density. The calculations were performed using analytical formulas for the Rayleigh scattering on a spheroid. Axis ratio larger than 1 corresponds to a prolate spheroid. Axis ratio lower than 1 corresponds to an oblate spheroid. Adopted from Myagkov et al. (2016a).*

potential of the methodology unexplored. Preliminary studies show that the vertical change of polarizability ratio can be used to infer the dominant microphysical growth process (riming/aggregation Myagkov et al., 2016b). Even though the STSR mode has been widely used in precipitation radar networks, there have been only a few studies using this mode in cloud radars (Myagkov et al., 2016a,b; Myagkov et al., 2020). Within the project SPOMC of SPP-PROM Phase I, the technique of Myagkov et al. (2016a) is currently being updated in order to be able to provide information about the hydrometeor ratio in clouds. To achieve this, the Doppler spectra of Z_{DR} and ρ_{HV} of STSR mode Ka-band radar observations from different elevation angles are screened for signatures of different types of hydrometeors. In case studies, it could already be shown that mixtures of prolate, isometric, and oblate hydrometeors can be detected using this extended polarimetric approach. By the end of SPP-PROM Phase I, the extended technique is expected to be applicable also to similar scans from other STSR-mode cloud radars.

Polarimetric observations with centimeter-wavelength radars often show K_{DP} signatures in deep cold precipitating clouds. The observed enhanced values of K_{DP} imply a high concentration of ice particles with highly non-spherical shape. The non-sphericity, however, is not visible in (integrated) Z_{DR}. Such situations indicate the presence of at least two distinct types of particles in the same volume: (1) small non-spherical particles with high concentration responsible for the enhanced K_{DP} and (2) large aggregates with no strong polarimetric signatures. Due to their much higher reflectivity, the aggregates dominate the backscattering polarimetric variables (e.g., Matrosov et al., 2020). Only radars capable of spectral-polarimetric observations can resolve the polarimetric signatures of different hydrometeor populations in the same volume and thus help to understand the origin of the small ice particles and their impact on cloud development and precipitation rates. Due to the inverse dependence on wavelength, W-band radars are more suited to detect small hydrometeors like cloud droplets and small ice particles and K_{DP} signatures are stronger than at centimeter-wavelength radars. Also, cloud radar resolution volumes are much smaller than that of weather radars making them more ideal for detailed microphysical retrievals. Findings based on cloud radar observations will also help improving operational hydrometeor identification schemes using weather radars.

In contrast to the majority of cloud radars, the polarimetric 94 GHz cloud radar owned by Leipzig University (LIMRAD94) is an STSR-polarimetric mode radar that combines Doppler and polarimetric observations. Specifically, the radar measures the set of backscatter polarimetric variables individually for each spectral component at a very fine Doppler resolution of a few cm s^{-1}. This enables a characterization of different particle populations coexisting in the same volume. Within this project, LIMRAD94 is planned to be equipped with a scanning unit to exploit the full potential of the radar.

Using a radar identical to LIMRAD94, Myagkov and Rose (2018) showed the potential to characterize small ice particles in the presence of aggregates: Fig. 2 shows an example of spectral observations in a deep precipitating cloud. The slower moving ice particles above the melting layer have enhanced values of Z_{DR} indicating strong non-sphericity. Based on such spectrally resolved observations, it is possible to estimate the polarizability ratio of the small ice particles. Further, assuming that observed K_{DP} values are solely caused by the small ice particles, their mass, size, and concentration can be estimated as illustrated in Myagkov and Rose (2018). The identification of small ice crystals has potential to identify SIP.

To obtain quantitative cloud property estimates from radar observations, machine learning methods are required to derive atmospheric variables from the measurements. Due to its ability to quantify the information content of the measurements, the Bayesian Optimal Estimation method (Rodgers, 2000; Maahn et al., 2020) is particularly useful to quantify the benefit of including novel measurements parameters (Maahn and Löhnert, 2017) such as spectral polarimetric variables. Also, Optimal Estimation can provide error estimates for the results and quantify information contents of measurements which allows for a thorough analysis of the retrieval's performance. Using inverse retrieval techniques requires using a forward operator that simulates the instrument's measurements based on the atmospheric state. The Passive and Active Microwave radiative TRAnsfer model

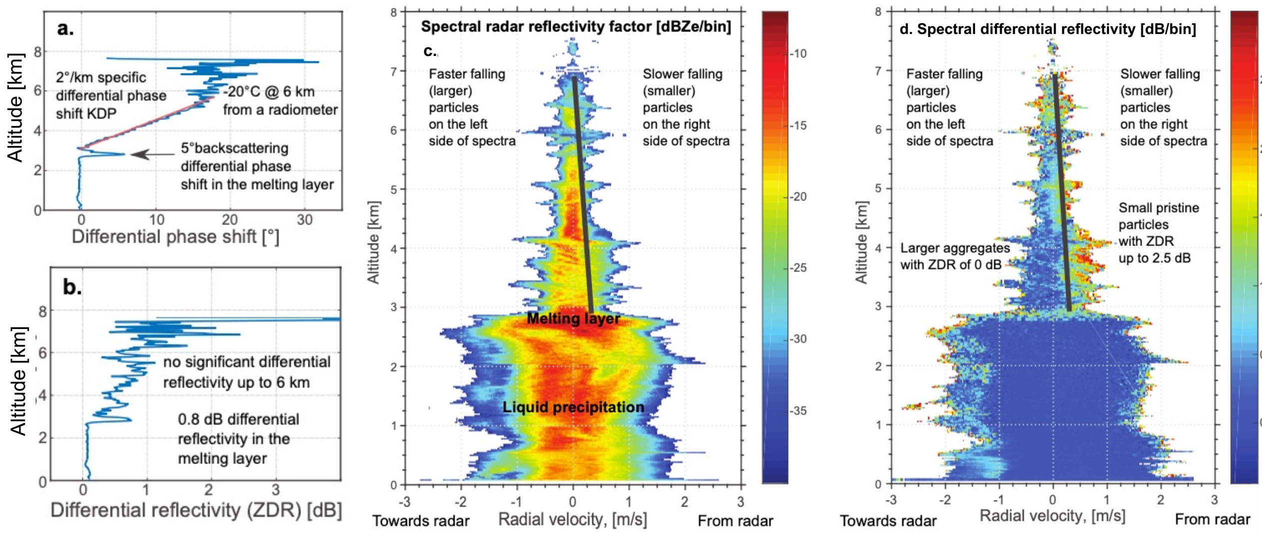

Figure 2: *Slanted profiles of differential phase shift (a), differential reflectivity Z_{DR} (b), spectral reflectivity factor (c), and spectral differential reflectivity (d) taken by a 94 GHz (W-band) radar similar to the LIMRAD94 at 10 UTC on 12 June 2018 at Meckenheim, Germany. The profiles were measured at 30° elevation. For the spectral plots (c, d), mean Doppler velocity has been removed individually for each altitude bin in order to mitigate the influence of horizontal air motions. The figure is adopted from a poster presentation by Myagkov and Rose (2018) given at ERAD2018. The melting layer is at 3 km altitude. Particles on the right side of the spectra are smaller (moving slower towards the radar) than those on the left side. Based on scattering calculations (not shown), K_{DP} values of 2° km $^{-1}$ (a) indicate the presence of small ice particles with relatively high ice density. Large aggregated or rimed particles would cause nearly-zero K_{DP} values. Even though small ice particles have high (up to 2–3 dB) values of Z_{DR}, their backscattering polarimetric signatures are masked by larger particles with Z_{DR} of 0.5–1 dB (b). The small ice particles are also not clearly visible in the Doppler spectrum (c) but the spectral differential reflectivity (d) indicates clearly the presence of small particles.*

(PAMTRA) is actively co-developed by the applicants (Mech et al., 2020) and is frequently used in combination with atmospheric models such as ICON (Heinze et al., 2017; Ori et al., 2020). For modeling the particle scattering properties, the T-Matrix (Mishchenko et al., 1996) approach is frequently used for polarimetric applications, but the required assumption of spheroidal particles can lead to biases for larger particles (Leinonen et al., 2012). Discrete Dipol Approximation (DDA, DeVoe, 1964) is the gold standard for estimating scattering properties of ice and snow particles, but due to its high computational costs it needs to be run offline and used through scattering databases (e.g., Liu, 2008). While these DDA-based scattering data bases can be used in principle for polarimetric applications, most data bases assume the particles to be randomly oriented so that most polarimetric signals vanish. Only recently, the US Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) program[3] released a suited database without this assumption. While the use of such scattering databases allows for simulating non-spherical particles at different wavelengths consistently from different viewing angles, including them in complex inverse retrievals might require interpolation leading to potential biases. This is because they require particle properties such as size and mass to be continuously adjustable, but only a finite number of discrete particles can be included in the database.

Besides a forward model, also a priori information is required for Optimal Estimation retrievals. For snowfall retrievals, optical snowfall imagers can provide such information by observing size, shape, mass and fall velocity distributions (Garrett and Yuter, 2014; Pettersen et al., 2020; Praz et al., 2017). Also, they have been used for estimating scattering properties (Gergely and Garrett, 2016) and the degree of riming (e.g., Grazioli et al., 2014; Hicks and Notaroš, 2019). For the MOSAiC experiment, a novel Video In Situ Snowfall Sensor (VISSS, Maahn et al., 2021, Fig. 3) was specifically developed by the applicants. This was motivated by limitations of current available sensors which either have a

[3]Publication in progress, database available at `https://www.arm.gov/data/data-sources/icepart-mod-120`

rather small measurement volume (MASC, Multi-Angle Snowfall Camera, Garrett et al., 2012), lower optical resolution (PIP, Precipitation Imaging Package, Newman et al., 2009; Pettersen et al., 2020) or combine a low optical resolution and a high wind sensitivity (2DVD, 2-dimensional video disdrometer Schönhuber et al., 2007). The cost efficient VISSS instrument combines relatively high resolution (59 μm/pixel), gray-scale images (Fig. 3) with a large measurement volume (8 x 8 x 6 cm), and an open design limiting wind disturbances. This combination is crucial when developing a priori information for sampling a sufficient number of particles and obtaining high quality particle properties.

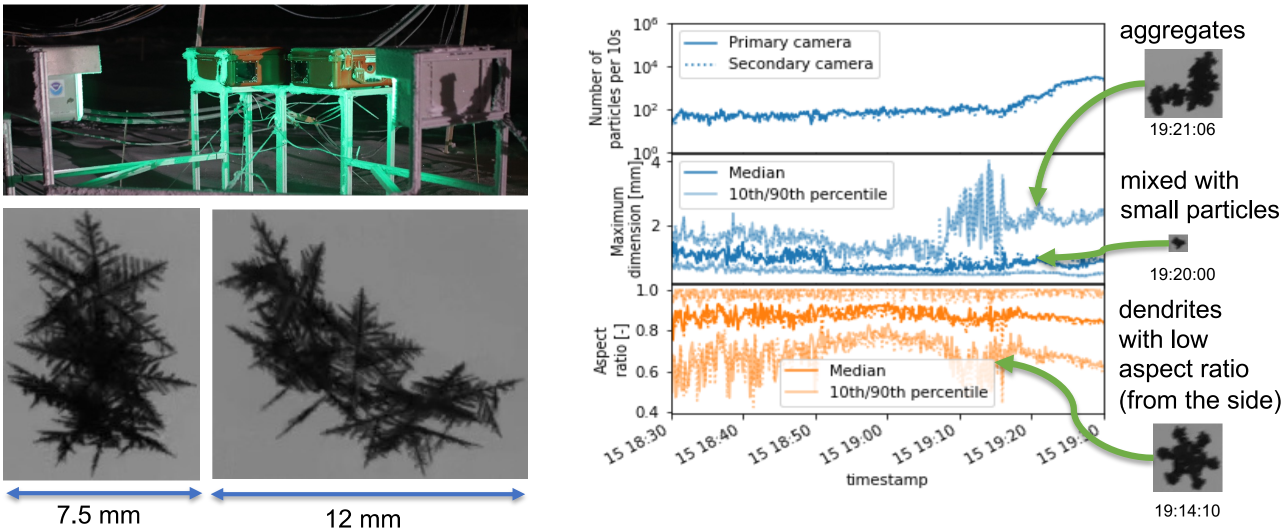

Figure 3: *Left: Video In Situ Snowfall Sensor (VISSS) during MOSAiC (picture M. Gallagher) with particle detected simultaneously by the two cameras. Right: Observed particles (top), maximum dimension (middle) and aspect ratio (bottom) for both VISSS cameras on 2020-04-15 with observed example particles.*

SAIL Field Experiment

The Surface Atmosphere Integrated Field Laboratory (SAIL, `https://sail.lbl.gov/research`) field campaign focusing on mountain hydrometeorology is led by principal investigator (PI) Daniel Feldman of Lawrence Berkeley National Laboratory, California. One main objective of the SAIL field experiment is to characterize the multi-scale dynamic and microphysical processes that control temporal and spatial distribution, phase, amount, and intensity of orographic and convective precipitation processes. The experiment will take place from Sep 2021 to June 2023 in the Upper Colorado River region around the Rocky Mountain Biological Laboratory (RMBL, 38°57'30.60"N, 106°59'15.72" W) near Crested Butte, Colorado. The ARM Mobile Facility 2 (AMF2) instrument suite will be deployed at 38°57'22.35"N, 106°59'16.66"W. Clouds will be observed using the AMF2 remote-sensing instruments, including a Ka-Band Zenith Radar (KAZR), a microwave radiometer, a high-spectral resolution lidar (HSRL), and a micropulse lidar (MPL). Additionally, the 3D wind field and its effect on snow redistribution will be characterized by observations with a Doppler lidar (DL), a radar wind profiler (RWP), radiosoundings, and distributed meteorological stations. Radiosondes will be launched at least twice daily to characterize the temperature and moisture structure of the atmosphere. This instrument suite will be enhanced by a scanning X-Band radar of the State University of Colorado (CSU) deployed at the slope of the Crested Butte Mountain Resort about 7 km South (S-SW) of RMBL (38°53'52.66"N, 106°56'35.21"W). Range Height Indicator (RHI) scans of the X-Band precipitation radar to the North toward the KAZR will yield dual-wavelength polarimetric radar observations to probe how hydrometeor microphyics and dynamics interact. With CORSIPP, we are planning participate in SAIL and will complement the observations with our STSR-mode W-band radar LIMRAD94 and the VISSS.

Previous experience of the applicants

Heike Kalesse-Los is the leader of the active remote sensing group at Leipzig University and has multiple years of experience in cloud-radar based observations, analysis, and creation of climatologies of cloud dynamics (Kalesse and Kollias, 2013) as well as process studies of cloud microphysics

(Kalesse et al., 2016a; Kalesse et al., 2016b) and Doppler spectrum information content exploitation (Kalesse et al., 2019; Kneifel et al., 2016) which will be expanded to scanning cloud radar observations within this project.

Maximilian Maahn joined Leipzig University in 2020 to establish a junior research group. He has a background in remote sensing and in situ measurements of snowfall and mixed-phase clouds (Maahn and Kollias, 2012; Maahn et al., 2014, 2019), inverse retrieval development (Maahn and Löhnert, 2017; Maahn et al., 2015, 2020), and developing radar forward operators (Mech et al., 2020). Recently, he developed the Video In Situ Snowfall Sensor (VISSS) that was successfully deployed during the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) experiment (Maahn et al., 2021). The current version of the VISSS retrieval software can already quantify particle size and shape, M. Maahn is currently finalizing the tracking algorithm required for measuring calibrated size distributions and fall velocity.

1.2 Project-related publications

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

Kalesse, H. et al. (2016a). "Fingerprints of a Riming Event on Cloud Radar Doppler Spectra: Observations and Modeling". In: *Atmos. Chem. Phys.* 16.5. DOI: 10.5194/acp-16-2997-2016.

Kalesse, H. et al. (2019). "Development and validation of a supervised machine learning radar Doppler spectra peak finding algorithm". In: *Atmos. Meas. Tech.* DOI: 10.5194/amt-2019-48.

Kalesse, H. and P. Kollias (2013). "Climatology of High Cloud Dynamics Using Profiling ARM Doppler Radar Observations". In: *J. Climate* 26.17. DOI: 10.1175/jcli-d-12-00695.1.

Luke, E. P. et al. (2021). "New Insights into Ice Multiplication Using Remote-Sensing Observations of Slightly Supercooled Mixed-Phase Clouds in the Arctic". In: *PNAS* 118.13. DOI: 10.1073/pnas.2021387118.

Maahn, M. and U. Löhnert (2017). "Potential of Higher-Order Moments and Slopes of the Radar Doppler Spectrum for Retrieving Microphysical and Kinematic Properties of Arctic Ice Clouds". In: *J. Appl. Meteor. Climatol.* 56.2. DOI: 10.1175/JAMC-D-16-0020.1.

Maahn, M. et al. (2020). "Optimal Estimation Retrievals and Their Uncertainties: What Every Atmospheric Scientist Should Know". In: *Bull. Amer. Meteor. Soc.* 101.9. DOI: 10.1175/BAMS-D-19-0027.1.

Mech, M. et al. (2020). "PAMTRA 1.0: The Passive and Active Microwave Radiative TRAnsfer Tool for Simulating Radiometer and Radar Measurements of the Cloudy Atmosphere". In: *Geosci. Model Dev.* 13.9. DOI: 10.5194/gmd-13-4229-2020.

1.2.2 Other publications, both peer-reviewed and non-peer-reviewed

Note that all publications listed here can be found in the appendix.

Kalesse-Los, H. et al. (2021). "Evaluating cloud liquid detection using cloud radar Doppler spectra in a pre-trained artificial neural network against Cloudnet liquid detection". In: *submitted to Atmos. Meas. Tech. Discuss.*

Maahn, M. et al. (2021). "Measuring Snowfall Properties with the Video In Situ Snowfall Sensor during MOSAiC". In: *EGU21 Abstr.* DOI: 10.5194/egusphere-egu21-3306.

Vogl, T. et al. (2021). "Using artificial neural networks to predict riming from Doppler cloud radar observations". In: *submitted to Atmos. Meas. Tech. Discuss.*

2 Objectives and work programme

2.1 Anticipated total duration of the project: Financial support is requested for 36 months.

2.2 Objectives

Our hypothesis is that in orographic conditions, where frequent updrafts occur, the FoO of riming and the FoO of SIP in mixed-phase clouds is different than in stratiform, non-convective clouds. We also speculate that an effect on snowfall rates during riming and SIP events is discernable.
These research hypotheses can only be addressed with state-of-the-art multi-sensor approaches and retrieval techniques. Building upon our experience on identifying riming processes in the SPP-PROM Phase I project PICNICC, we propose to combine ground-based remote-sensing and in-situ observations to identify and characterize riming and SIP events. Specifically, we will exploit the potential of using spectral polarimetric variables of an STSR radar (LIMRAD94) for gaining insights into microphysical cloud processes related to riming and SIP. The analysis will be supported by in-situ snowflake VISSS observations and the extensive instrumentation of the DOE ARM AMF2. This allows for combined multi-frequency vertically-pointing and scanning polarimetric Doppler cloud radar observations, in combination with backscatter lidar and microwave radiometer (MWR) measurements.

Our proposal will target the science objective I of SPP-PROM Phase II ”Exploitation of radar polarimetry for quantitative process detection in precipitating clouds and for model evaluation”. Specifically, we will focus on improving the understanding of riming and SIP processes in complex terrain by addressing the following research goals:

- **Goal 1:** Determine the frequency of occurrence of riming and secondary ice production at an orographically-influenced site
- **Goal 2:** Determine the influence of riming and secondary ice production on snowfall rates at an orographically-influenced site
- **Goal 3:** Characterize external drivers for riming and secondary ice production processes and snowfall rates
- **Goal 4:** Advance the PAMTRA radar forward operator to improve the polarimetric modeling of ice particles.

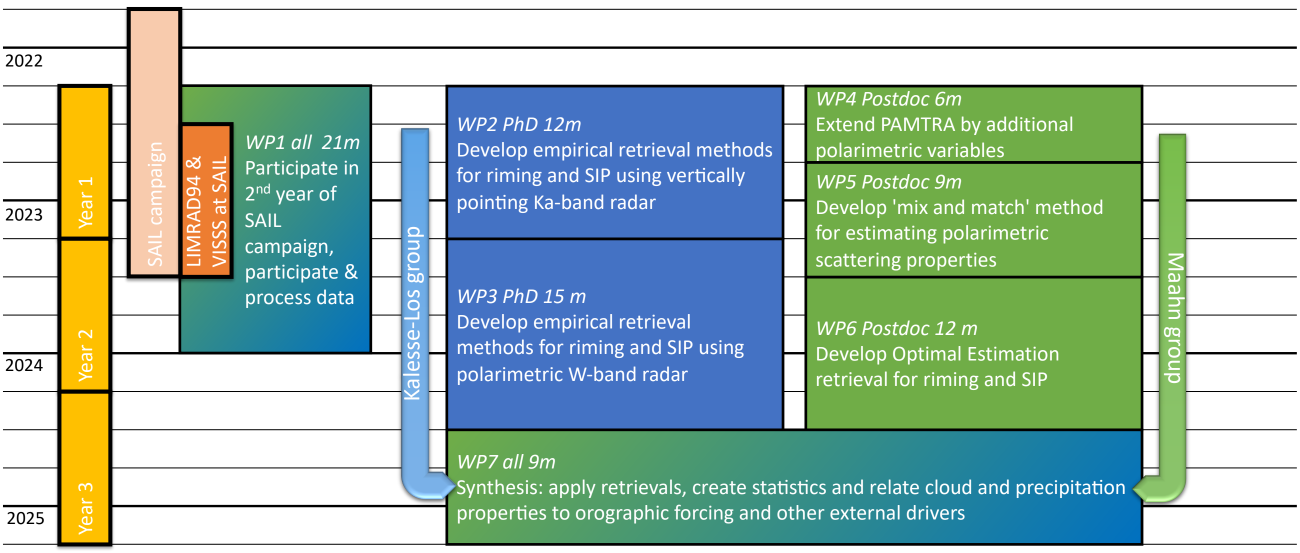

Figure 4: *Structure and time schedule for CORSIPP*

Results from CORSIPP will set the stage for an improved parameterizations of ice microphysical processes in atmospheric models which will be addressed in a follow up project.

2.3 Work programme including proposed research methods

We will tackle the research goals from two sides (Fig. 4): While **WP2-3** (Kalesse-Los group) are attempting to observe the relevant cloud microphysical processes using empirical relations qualitatively, **WP4-6** (Maahn group) will attempt to develop an inverse retrieval method aiming to quantify these methods. Combining both approaches will allow us to give more stringent constraints on riming and SIP.

WP1 Participation in the SAIL field experiment (all): We are planning to participate in the SAIL field experiment for one entire winter season from September 2022 to May/June 2023. Due to the expected high amounts of snowfall, we will be able to get statistical results of conditions conducive to riming and SIP in orographic conditions. Joining the SAIL campaign will not only allow for synergy effects with respect to instrumentation (KAZR, X-band radar, etc.), but also with respect to the analysis through collaboration with the ARM community (e.g., D. Feldman, M. Kumjian). Specifically, we will deploy a

- W-band polarimetric scanning Doppler cloud radar LIMRAD94 (RPG-FMCW-94-DP)
- 2nd generation Video In-Situ Snowfall Sensor (VISSS) developed by M. Maahn

These instruments will help to characterize precipitation formation and development (radar) and precipitation phase, amount, and distribution on the ground (VISSS). Beyond the objectives of CORSIPP, the W-band radar and the VISSS will fill a crucial gap in the setup of the SAIL campaign where the deployment of a W-band radar or an advanced optical snowfall sensor is not planed yet. The W-band operations will be supported by A. Myagkov (RPG) who will provide in-kind support in terms of optimization of observation settings and scanning patterns during the measurement campaign. We propose to extend the radar with a scanning unit so that we can do range height indicator (RHI) scans towards the KAZR. This allows combining the zenith-pointing Ka-band measurements with the slanted W-band measurements. We suggest to build an updated VISSS similar to the one build for the DFG funded (AC)^3 project (`http://www.ac3-tr.de`, Wendisch et al., 2017) for deployment in Ny-Alesund, Svalbard. In comparison to the original VISSS developed for the MOSAiC expedition, the 2nd generation VISSS features better resolution (42 instead of 59 μm) at a higher frame rate (187 instead of 140 frames per second) at a greater working distance (600 instead of 227 mm) making the measurement even more resilient with respect to wind induced turbulence which is pertinent in complex terrain. The VISSS data will be processed using the standard data processing providing estimates of particle size, aspect ratio and fall velocity distributions.

We will get logistical support from RMBL and the ARM-engineering team for the continuous operation of our W-band radar and VISSS after the installation. A proposal to receive guest instrument support by ARM is in preparation and will be submitted shortly.

WP2 Develop empirical methods to identify riming and SIP in vertically pointing radar measurements (PhD): Firstly, we will detect the presence of supercooled liquid—a prerequisite to riming—by using the cloud radar Doppler spectra based supercooled-liquid droplet identification technique of Luke et al. (2010) which has been used in Kalesse-Los et al. (2021) and is currently adapted to sites where orographic waves hinder the direct use of MDV as input to the ANN in the Kalesse-Los group (PhD Thesis W. Schimmel). Secondly, we will employ the novel riming identification approach of Vogl et al. (2021) developed within the SPP-PROM Phase I project PICNICC. Due to our focus on snow formation processes, we limit our analysis to solid precipitation thus mitigating radar

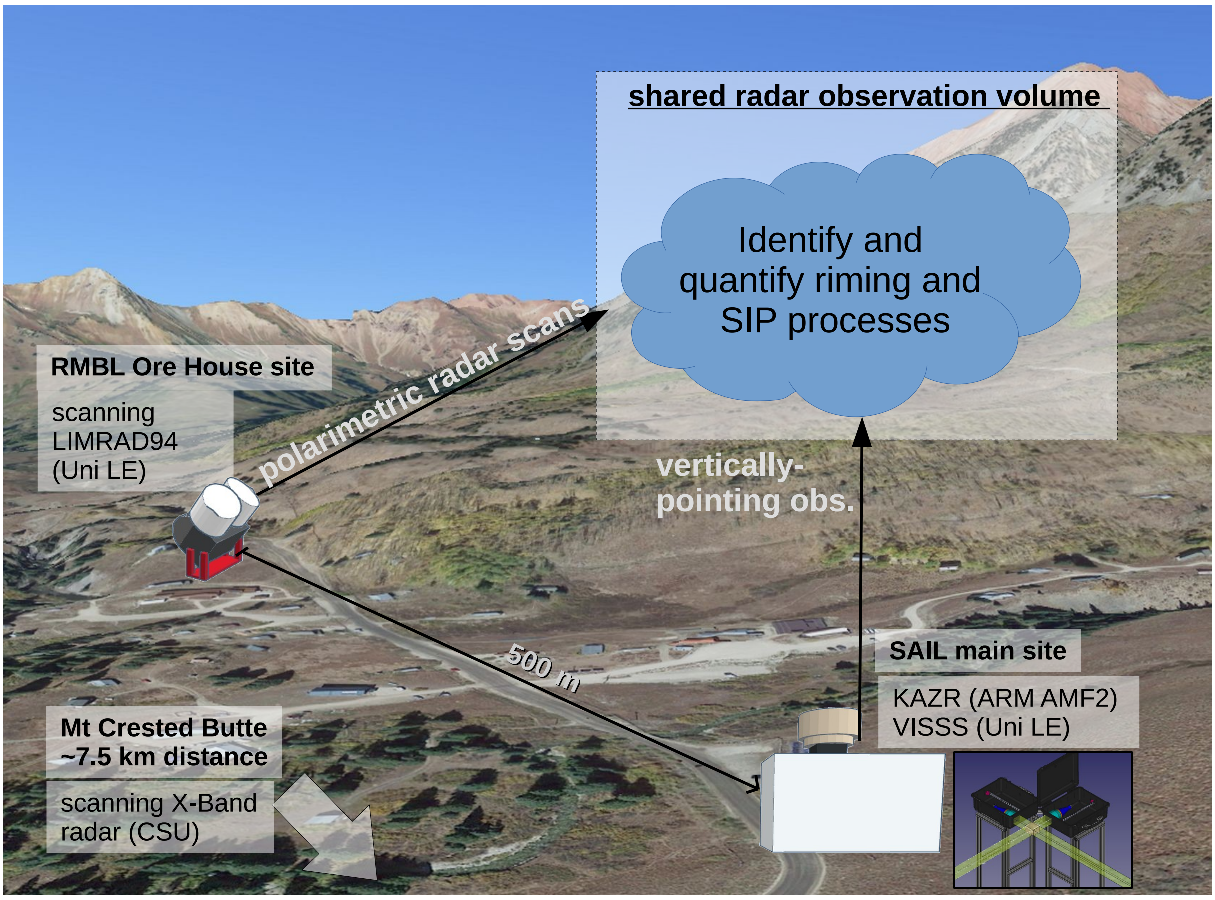

Figure 5: *Google maps view of the main SAIL site. Location of W-band LIMRAD94 and the ARM AMF2 site with the KAZR are shown and the main work packages of CORSIPP are illustrated.*

signal attenuation effects caused by the melting layer and rain. In our setup, the VISSS will provide a means to evaluate the quality of this riming retrieval. For both retrievals, we will use zenith-pointing KAZR Doppler spectra observations obtained starting in the first year of SAIL (start: September 2021). Crucial vertical air motion information needed for radar Doppler velocity value-based particle type assessment will be derived using data from radiosondes, DL, RWP, and—where possible—based on Doppler spectra liquid peak identification itself (Luke et al., 2010; Radenz et al., 2019; Shupe et al., 2004; Kalesse et al., 2016a, 2019). Ice needles formed by rime-splintering and supercooled drizzle will be identified using radar reflectivity and LDR using the classification method by Luke et al. (2021). SIP will be identified based on ice multiplication factors derived from spectral radar reflectivity as in Luke et al. (2021). In collaboration with D. Moisseev (U Helsinki), we will use INP parameterizations (DeMott et al., 2010; Schneider et al., 2021) to evaluate the ice multiplication factors derived with the approach by Luke et al. (2021).

WP3 Develop empirical methods to identify riming and SIP in polarimetric scanning radar measurements (PhD): For **WP3**, we have two main goals with respect to the two target processes of CORSIPP. For riming, we want to use the method from Myagkov et al. (2016a) to get vertical profiles of the polarizability ratio for the region of the strongest return in the Doppler velocity spectrum. In this way, we will be able to track and analyze changes in shape and density of largest particles from cloud top (where we expect "pristine" ice crystals not affected by aggregation/riming) to cloud bottom (where we expect the maximum accumulated effect of aggregation/riming). Since the vertical profiles are sensitive to changes in microphysical properties of the large particles, we want to check whether or not the vertical gradients have a relation to environmental conditions. For example, we expect that strong changes in polarizability ratio are triggered by the presence of supercooled liquid which is a prerequisite for riming. Because the change in polarizability ratio can be influenced by both, aggregation and riming, we will use the results of **WP2** to identify riming. For the first time, using the VISSS observations, we will be able to correlate the polarizability ratio gradients with in situ observations of hydrometeors at the surface.

With respect to SIP, the goal is to characterize small-size particles using the spectral polarimetric approach from Myagkov and Rose (2018). Because K_{DP} is sensitive to high number concentrations of small particles, we will use K_{DP} to identify cloud areas of interest for SIP. For these areas, we will use spectral Z_{DR} to separate Doppler spectra into two fractions: large ice particles (aggregates/rimed) and small ice particles. Based on the cloud radar polarimetric measurements, we will be able to characterize the small ice particles potentially created by SIP. For this, we will retrieve the polarizability ratio and use this information with different ice density assumptions for simulating scattering properties using the T-matrix approximation. For these small particles, the T-Matrix approximation will be still sufficient, but the use of particles from DDA databases will be tested for consistency (see **WP4**). Assuming that K_{DP} is solely caused by the observed small ice particles, the simulations can be used to estimate their mass, but also ranges of size and number concentration. Derived particle concentrations will hint to SIP occurrence.

Realizing this approach will be done in collaboration with the developer of the approach A. Myagkov (RPG). Results of **WP2** and **WP3** will be discussed with the PROM II project POMODORI by S. Kneifel (U Cologne) who focuses on the refinement of understanding riming signatures in polarimetric observations at different frequencies (W-Band, C-Band). Events of riming and SIP identified via **WP2** and **WP3** will be combined into a database of cases which will further be used in **WP7**.

WP4 Extend PAMTRA for additional polarimetric variables (Postdoc): Due to its ability to simulate the full radar Doppler spectrum and due to its basic polarmetric capabilities, PAMTRA (Mech et al., 2020) is the ideal radar forward simulator for CORSIPP. While Z_{DR} and LDR are already implemented in PAMTRA, we will extend PAMTRA with spectral ρ_{HV} and δ as well as (non spectral) K_{DP} capabilities (Ryzhkov et al., 2011) to reach **Goal 4**. This will close an important gap in PAMTRA's capabilities, also due to the widespread use of PAMTRA for comparing ICON simulations with radar observations (Heinze et al., 2017; Ori et al., 2020).

To raise PAMTRA to full polarimetric potential without relying on the T-Matrix approach, a scattering data base that contains non-randomly oriented particles needs to be implemented. For this, we will use the 'Polarimetric Scattering Database for Non-spherical Ice Particles at Microwave Wavelengths' database provided by the DOE ARM program. The data base contains 1779 different ice particle types such as aggregates, branched planar crystals, plates, columns, and conical graupel. This will allow to model the polarimetric scattering properties for the different particle types. We will also closely collaborate with the SPP PROM phase II project 'PRISTINE' by D. Ori (U Cologne) that is targeted at developing a novel advanced scattering data base to make sure potential advances will be applied to CORSIPP as well. Also, we will work with SPP PROM phase II project 'FRAGILE' by S. Kneifel (U Cologne) who is also looking into polarimetric signatures of ice particles using C-band radar observations.

WP5 Develop 'mix to match' method for estimating polarimetric scattering properties (Postdoc): Embedding PAMTRA into an Optimal Estimation framework will require to obtain scattering properties for specific particle sizes and particles mass. This is not possible when using scattering data bases that provide properties of discrete particles. To overcome this problem, we will develop a 'mix to match' method where we will combine different particles from the scattering database in a way that their bulk properties (size, mass) match the desired particle properties. We assume that this approach is more consistent to the natural variability of snow particles than a nearest neighbor approach or interpolating scattering properties. To make sure PAMTRA does not produce inconsistent scattering properties and to evaluate the new 'mix to match' method, we will attempt a closure of a) the vertically pointing 35 GHz KAZR measurements (including LDR), b) the slanted 94 GHz W-band non-polarimetric and polarimetric measurements, and c) the optical VISSS measurements to the extend possible. Since the beam volumes of both radars won't be exactly matched, thresholds for spatial homogeneity will be derived from temporal variability; only data of cases with sufficient spatial variability will be used. The slanted W-band spectra will be corrected for horizontal wind using the KAZR and interpolated onto the KAZR's Doppler resolution. By this, the spectral radar observations of KAZR and W-band can be combined. Obtaining such a closure will give us confidence that PAMTRA's scattering properties are not biased.

WP6 Develop Optimal Estimation retrieval for quantifying riming and SIP processes (Postdoc): Based on the optimized PAMTRA forward operator (**WP4**) and the mix to match technique (**WP5**), we will develop a machine learning algorithm for quantifying cloud and precipitation properties based on the Bayesian Optimal Estimation concept (Rodgers, 2000; Maahn et al., 2020). The goal is to use the experience gained in **WP2** and **WP3** for identifying riming and SIP processes to develop a retrieval that can quantify the associated changes with respect to ice particle number concentration and density. For now, we do not strive to develop a retrieval that is applicable in all conditions, but specifically for the clouds during SAIL where riming and SIP processes take place. Based on the identification of hydrometeor populations in **WP2**, we will identify up to three hydrometeor populations in the radar Doppler spectrum to distinguish between liquid droplets, smaller pristine ice particles as produced by SIP, and larger complex, potentially rimed ice particles. For each identified particle type, we will retrieve particle properties such as number concentration, size, and ice density using the radar retrieval framework developed by Maahn and Löhnert (2017). We will carefully evaluate which state vector variables are required, which simplifying assumption can be made (e.g., that small ice particles have a fixed density), and exploit correlations between variables. As an input, we will use the combined radar observations: from the KAZR, we will use radar reflectivity and mean Doppler velocity, and—to the extent possible for multi modal peaks—higher moments as well as slopes of the radar Doppler spectrum following Maahn et al. (2015) and Maahn and Löhnert (2017). Different to other retrieval studies, we will estimate the moments for up to three sub peaks (related to the up to three hydrometeor types) separately even when the peaks are not fully separated (Kalesse et al., 2019; Radenz et al., 2019). From the W-band radar, we will use reflectivity, K_{DP}, Z_{DR}, ρ_{HV} and—for exploiting the signatures of pristine particles shown in Fig. 2.d—skewness and/or slopes of the spectral differential reflectivity. The benefit of including additional, polarimetric variables into the retrieval will be quantified with an information content study (Maahn and Löhnert, 2017). Using Optimal Estimation also allows a thorough treatment of uncertainties (Maahn et al., 2020), this includes correcting the radar Doppler spectra for air motions. The prior required for the retrieval will be designed following Maahn et al. (2015). It will be based on the VISSS observations (**WP1**) and results form previous studies (e.g., Rémillard et al., 2017). Based on the retrieved state, we can diagnose SIP by an increase in number concentration of small particles and diagnose riming by an increase of mass for larger particles. As a side effect, we can diagnose a snowfall rate from these variables which will further be used in **WP7** (**Goal 2**). In **WP7**, we will collaborate closely with M. Kumjian (PennState) who is very experienced with radar based Bayesian retrievals (Lier-Walqui et al., 2020). The goal of **WP7** is to allow an objective, quantitative observation of SIP and riming processes for the SAIL campaign. By retrieving quantities that are also found in advanced atmospheric models (particle size distribution, particle mass), the results of **WP6** open the door for a detailed model evaluation of riming and SIP processes.

WP7 Synthesis: apply retrievals, create statistics and relate cloud and precipitation properties to orographic forcing and other external drivers (PhD and Postdoc): Combining the qualitative approach of **WP2** and **WP3** with the quantitative approach of **WP6**, the FoO of riming and SIP (**Goal**

1) and their influence on snowfall rates (**Goal 2**) at the RMBL-site will be determined. Also, external drivers conducive to riming and SIP and their effect on snowfall rates including dynamics (updraft strength and turbulence from Doppler lidar and radar wind profiler observations and cloud radar MDV variance), profiles of temperature and relative humidity as derived from radio soundings, liquid water path determined from MWR observations, and cloud type (stratiform/convective using the classification by e.g., Mosimann 1995) will be characterized (**Goal 3**) by means of correlating the drivers with the FoO of the processes. For the latter, we can rely on the comprehensive observational set of the SAIL campaign. Reaching the four CORSIPP goals will enhance the understanding of two microphysical key processes for snowfall formation, namely riming and SIP. The results will be compared with the PROM II project 'POMODORI' by S. Kneifel (U Cologne) who is studying riming and SIP using different methods in Germany to identify the effect of methodology and site (orographic site and flat terrain) on the results.

Time considerations See Fig. 4 for detailed time planning.

3 Bibliography concerning the state of the art, the research objectives, and the work programme

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4 Relevance of sex, gender and/or diversity

The positions in this project will be selected without regard to sex, gender, religion, national origin, political affiliation, marital or family status or other differences. The applicants strive to create an inclusive and diverse work environment.

5 Supplementary information on the research context

5.1 Ethical and/or legal aspects of the project: Not applicable

5.2 Data handling

All measured observations will be made openly available in the repository of the ARM facility which is the central repository for the SAIL campaign. Code used for the data analysis will be made freely available on GitHub.

5.3 Other information

In submitting a proposal to the DFG, we agree to adhere to the DFG's rules of good scientific practice and the FAIR guiding principles (Wilkinson et al., 2016).

6 People/collaborations/funding

6.1 Employment status information

Kalesse-Los, Heike – Jun.-Prof. (limited-term civil servant position with tenure track)
Maahn, Maximilian – Junior group leader (base funding until June 2026, Wissenschaftlicher Mitarbeiter)

6.2 First-time proposal data: Not applicable

6.3 Composition of the project group

The following individuals will work on the project but will not be paid out of the project funds:
H. Kalesse-Los, M. Maahn (Leipzig University)

6.4 Researchers in Germany with whom you have agreed to cooperate on this project

Dr. Alexander Myagkov, RPG, Meckenheim (**WP1**, **WP3**)
Dr. Stefan Kneifel, U Cologne (**WP3**, **WP4**, **WP7**)
Dr. Davide Ori, U Cologne (**WP4**, **WP5**)
Dr. Patric Seifert, TROPOS (**WP3**)

6.5 Researchers abroad with whom you have agreed to cooperate on this project

Dr. Dmitri Moisseev, University of Helsinki, Finland (**WP2**, **WP7**)
Dr. Daniel Feldman, Lawrence Berkeley National Lab, USA (**WP1**, **WP7**)
Dr. Matthew Kumjian, Pennsylvania State University, USA (**WP1**, **WP6**, **WP7**)

6.6 Researchers with whom you have collaborated scientifically within the past three years

Claudia Acquistapace (U Cologne), Boris Barja (U de Magallanes), Jennifer Comstock (PNNL), Christopher Cox (CU Boulder), Jessie Creamean (CU Boulder), Susanne Crewell (U Cologne), Gijs de Boer (CU Boulder), Kerstin Ebell (U Cologne), Graham Feingold (NOAA Boulder), Yan Feng (Argonne), Irina Gorodetskaya (U Aveiro), Fabian Hoffmann (CU Boulder), Stefan Kneifel (U Cologne), Pavlos Kollias (Stony Brook), Mark Kulie (NOAA Wisconsin), Ulrich Löhnert (U Cologne), Edward Luke (Brookhaven), Gerhard Mace (U Utah), Sergey Y. Matrosov (CU Boulder), Allison McComiskey (Brookhaven), Mario Mech (U Cologne), Dmitri Moisseev (U Helsinki), Davide Ori (U Cologne), Derek Posselt (JPL), Alexander Ryzhkov (U Oklahoma), Vera Schemann (U Cologne), Patric Seifert (TROPOS), Matthew Shupe (CU Boulder), Amy Solomon (CU Boulder), David Turner (NOAA Boulder), Annakaisa von Lerber (FMI), Christine Wiedinmyer (CU Boulder), Christopher Williams (CU Boulder)

6.7 Project-relevant cooperation with commercial enterprises: None.

6.8 Project-relevant participation in commercial enterprises: None.

6.9 Scientific equipment

94 GHz RPG W-Band FMCW Dual-Pol STSR Doppler cloud radar (currently without scanner). Equipment for data storage, processing and visualisation, both for observational and model data, is available at the Leipzig Institute for Meteorology, Leipzig University.

6.10 Other submissions: None.

7 Requested modules/funds

7.1 Basic Module

7.1.1 Funding for Staff

The PhD student will work on **WP2** and **WP3** and will support **WP1** and **WP7** . The student assistants will support the project with respect to documentation, data processing, and quality control of the LIMRAD94 data.

Research associate (PhD), TV-L 13 75 %, 36 months	36 × 4368.75 €
Student assistant (12 months)	12 × 450.00 €
Total Funding for staff (Kalesse-Los group)	162 675.00 €

The Postdoc will work on **WP4**, **WP5** and **WP6** and will support **WP1** and **WP7** . Due to the ambitious goals of the WPs with respect to model and retrieval development, we request a Postdoc. The student assistants will support the project with respect to documentation, data processing, and quality control of the VISSS data.

Research associate (Postdoc), TV-L 13 100 %, 36 months	36 × 6300.00 €
Student assistant (12 months)	12 × 450.00 €
Total Funding for staff (Maahn group)	232 200.00 €

7.1.2 Direct Project Costs

7.1.2.1 Equipment up to 10 000 €, Software and Consumables

For measuring snowfall properties at the ground, an optical snowfall sensor is required. We propose to build a 2nd generation VISSS based on the experiences with the original VISSS for MOSAiC (owned by CU Boulder) and the VISSS that is currently build at U Cologne in collaboration with the applicants for the (AC)^3 project for deployment in Ny-Alesund, Svalbard. The following components are required to build a 2nd generation VISSS by the Maahn group:

Telecentric lens SILL TZM 1235/0,083-C	2 × 2900.00 €
Camera DALSA GENIE NANO-5G-M2050	2 × 3300.00 €
LED backlights Smartvision ODMOBL-150X150-530	2 × 2250.00 €
Data acquisition system	2 × 2750.00 €
Transport boxes	2400.00 €
Aluminum profile frame	1800.00 €
Small Parts (housing, power supplies, heating, cables, etc.)	5000.00 €
Total Equipment up to 10 000 €, Software and Consumables (Maahn group)	31 600.00 €

7.1.2.2 Travel Expenses

For the PhD of the Kalesse-Los group, we apply for each 3,000 € per year for travel to one international and one national conference or meeting. PI conference travel is supported by base funding. We apply for campaign travel for the PhD to participate in SAIL:

Conference travel (per diem, travel, housing, conference fees)	3 × 3000.00 €
Campaign travel (3+1 weeks for set up and packing, per diem, travel, RMBL housing)	6000.00 €
Total Travel Expenses (Kalesse-Los group)	15 000.00 €

We apply for the same travel expenses for the Postdoc of the Maahn group:

Conference travel (per diem, travel, housing, conference fees)	3 × 3000.00 €
Campaign travel (3+1 weeks for set up and packing, per diem, travel, RMBL housing)	6000.00 €
Total Travel Expenses (Maahn group)	15 000.00 €

7.1.2.3 Visiting Researchers (excluding Mercator Fellows): none

7.1.2.4 Expenses for Laboratory Animals: none

7.1.2.5 Other Costs

For participation in the SAIL experiment, the following costs for site planning, instrument shipment, and installation are applied for. Travel costs for the experiment are listed in the Travel Expenses section. An indirect rate of 50 % is applied to all RMBL services, except for the Planning and Renewal Fees, as per the RMBL negotiated rate with the US National Science Foundation (see attached RMBL quote). Quotas in US Dollar are converted to Euro based on exchange rate of 1 USD = 0.83 Euro from 26.4.21. Note that for simplicity, RMBL related costs for the deployment of the W-band radar and the VISSS are not separated but treated together in the budget of the Kalesse-Los group:

W-band radar LIMRAD94 shipping costs Colorado	5000.00 €
RMBL site-planning and approvals	5447.00 €
RMBL project services management	415.00 €
RMBL site preparation/tree removal	166.00 €
RMBL electrical power and telecommunication infrastructure	1245.00 €
RMBL technician station fees	847.00 €
RMBL forklift for installation and decommissioning (delivery and rental)	2 × 1411.00 €
RMBL wooden platform to elevate radar above snow pack	1826.00 €
RMBL electrical power service	3174.00 €
RMBL indirect costs	4824.00 €
Liquid nitrogen for radar calibration	1000.00 €
2 sets of radar radome replacement sheets	900.00 €
Dry storage for shipping boxes	1000.00 €
Total Other costs (Kalesse-Los group)	28 666.00 €

While all RMBL related cost for the VISSS deployment are already accounted for in the budget of the Kalesse-Los group as stated above, we separately apply for shipping the VISSS to Colorado:

VISSS shipping costs Colorado	2000.00 €
Total Other costs (Maahn group)	2000.00 €

7.1.2.6 Project-related publication expenses

We apply for a total of 2250 € for publication expenses per group (750 € per year).

Total Publication costs (Maahn group)	2250.00 €
Total Publication costs (Kalesse-Los group)	2250.00 €

7.1.3 Instrumentation

7.1.3.1 Equipment exceeding 10 000 €: None.

7.1.3.2 Major Instrumentation exceeding 50 000 €

Because no polarimetric measurements are possible with the current radar configuration, we are applying for a radar scanning unit to perform the illustrated polarimetric radar measurements. This will also allow for collocated measurements with the ARM KAZR radar. The radar is manufactured by RPG and only RPG is constructing appropriate radar scanning units.

2D scanning unit for 94 GHz radar	107 540.00 €
Total Equipment exceeding 50 000 € (Kalesse-Los group)	107 540.00 €

8 List of attachments

- Curriculum Vitæ, Heike Kalesse-Los
- Curriculum Vitæ, Maximilian Maahn
- Offer for 94 GHz radar scanning unit and justification letter for not submitting comparative offers
- RMBL site cost estimate
- Letters of support (D. Feldman, M. Kumjian, D. Moisseev, A. Myagkov, P. Seifert)
- Myagkov and Rose (2018), Kalesse-Los et al. (2021), Maahn et al. (2021), Vogl et al. (2021).