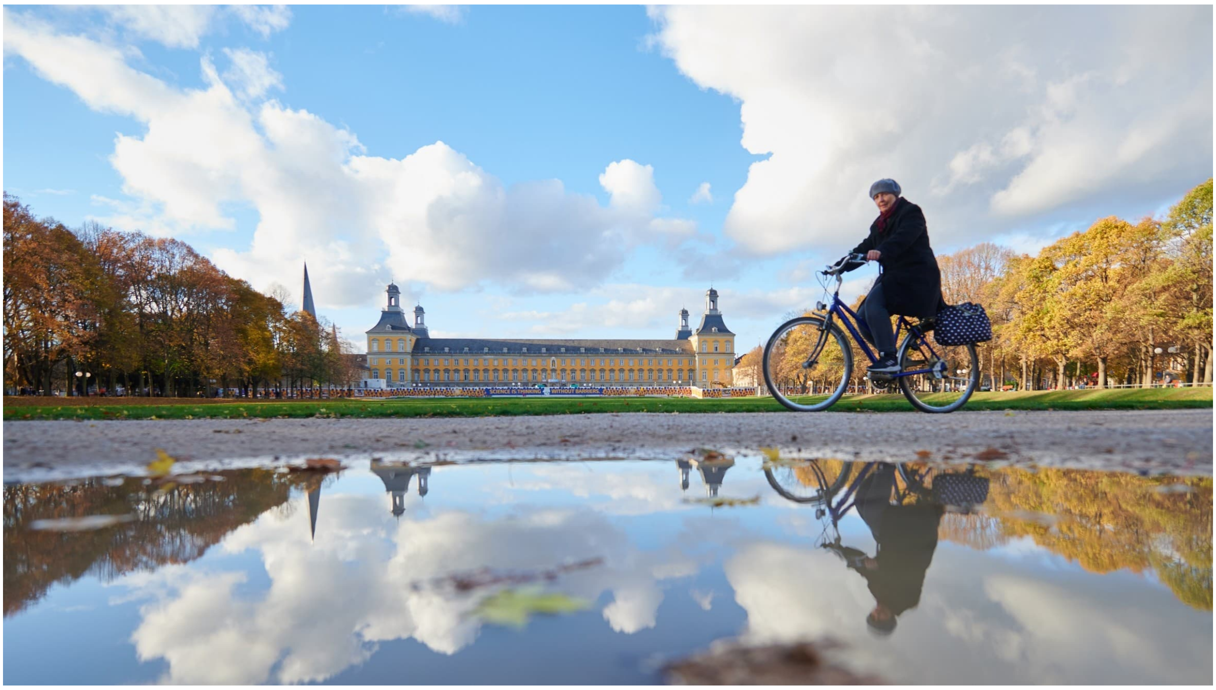
# PrePEP Conference

## Precipitation Processes - Estimation and Prediction

# Book of Abstracts



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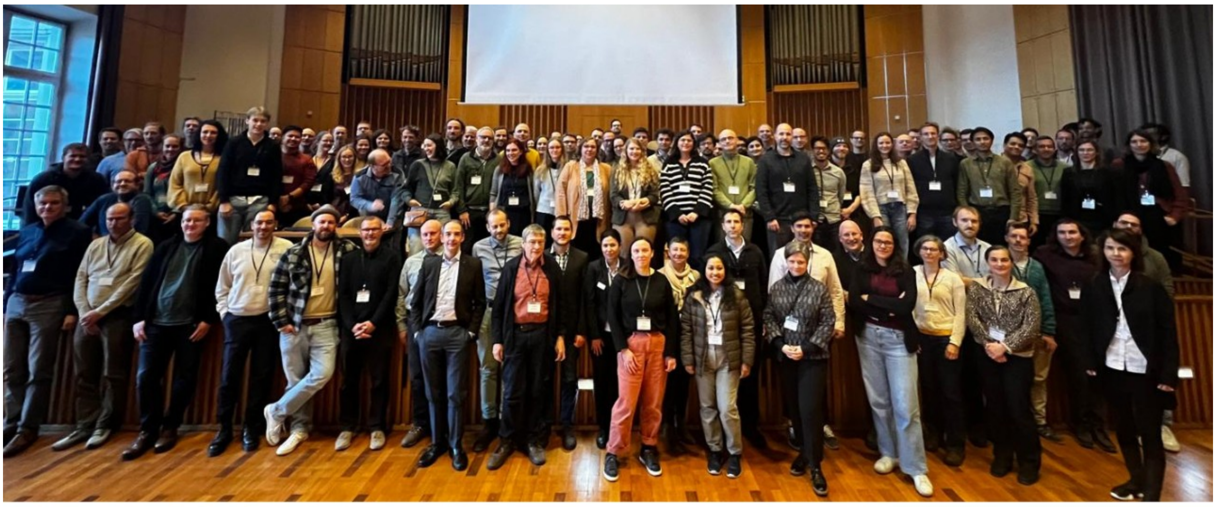
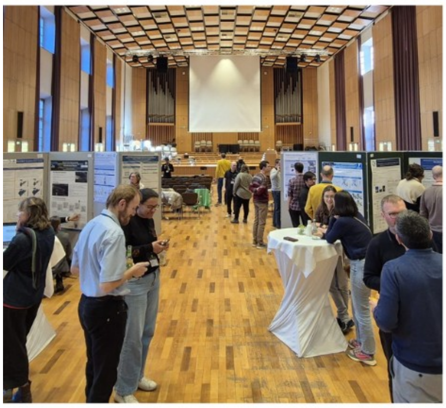
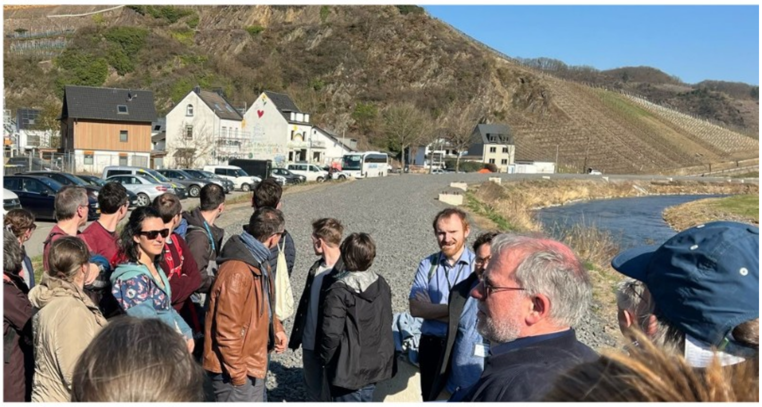
16–21 March 2025

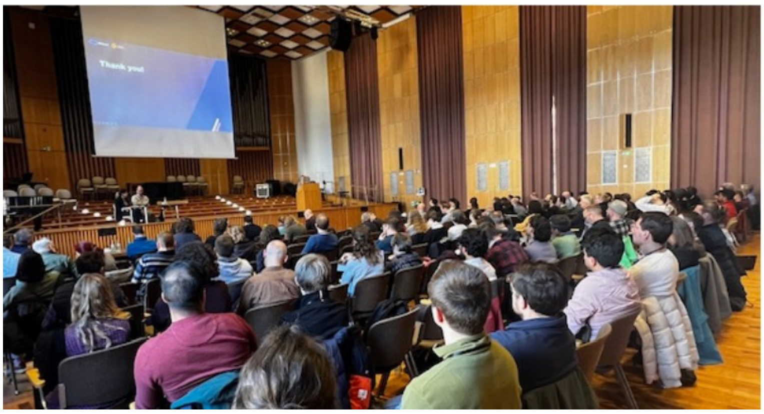
University of Bonn

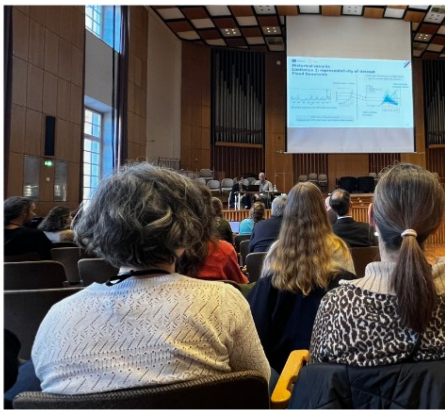
The conference **Precipitation Processes - Estimation and Prediction (PrePEP)** discussed multi-sensor, newly emerging, and opportunistic in-situ and remote sensing techniques to better understand and monitor precipitation processes. Central topics of the PrePEP conference have been methodologies for exploiting observations for retrievals, nowcasting, data assimilation and parametrization development for NWP models as well as blending and probabilistic techniques towards seamless prediction including hydrological forecasts. Additional key elements of **PrePEP** have been a better understanding, assessment, and prediction of extreme precipitation events and floods.
The PrePEP conference started on 16 March 2025 with short courses followed by keynotes and oral presentations from 17 to 21 March, a poster session on 18 March and an excursion to the Ahr valley on 19 March. Presentations and material of the authors who have given their consent can be found in the weekly schedule on the conference homepage (https://indico.scc.kit.edu/e/prepep).











## Organizers

The conference on **Precipitation Processes – Estimation and Prediction (PrePEP)** was organized by representatives of the following projects:

**The research unit on "Near-Realtime Quantitative Precipitation Estimation and Prediction" (RealPEP, RU-2589), funded by the Deutsche Forschungsgemeinschaft (DFG),**

**the DFG-funded special priority program "Polarimetric Radar Observations meet Atmospheric Modelling" (PROM, SPP-2115), and**

**the development project on a "Seamless Integrated Forecasting System" (SINFONY) of the German Meteorological Service (DWD).**

**The organizers also like to express their sincere gratitude to the University of Bonn for generously providing the venue, technical support, and logistical assistance for this conference.**

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# Contents

**Keynotes** .......... **10**

The amazing journey through an opportunistic satellite sensing system: from the 'bad-looking' raw data to the 'handsome' precipitation estimate .......... 10

Flood forecasting in Bavaria: Organization of the flood information service (HND) and limits of early warning due to model uncertainties discussed on the basis of examples from the 2024 flood event in Swabia .......... 11

On the importance of precipitation datasets for operational hydrological monitoring and forecasting .......... 12

Flash floods predictions and mitigation under change – challenges, models, perspectives 13

Advancing Precipitation Estimation and Prediction through Deep Learning at Météo-France .......... 14

Precipitation nowcasting: from Lagrangian models to advanced ML approaches .......... 15

How ML is transforming our approach to seamless weather forecasting .......... 16

Nowcasting extreme rainfall over the UK .......... 17

Making use of supplementary observations for the development of physical parameterizations .......... 18

**Session 1.A: From classical to integrated remote sensing. New observation strategies for clouds and precipitation (multi-frequency, spectral polarimetry, multi-sensor)** .......... **19**

Weather radar adjustment with pyRADMAN: Experiments with and without commercial microwave links .......... 20

Tropical rainfall nowcasting with Commercial Microwave Links: opportunities and current limitations .......... 21

Urban surveillance camera for urban extreme rainfall estimation .......... 22

Achievments of the COST Action on Opportunistic Precipitation Sensing (OpenSense) . 23

Rainfall estimation over the San Francisco Bay Area: a new system to infuse microphysical information into QPE .......... 24

Deep Learning for Multimodal Precipitation Estimation: From Research to Operationalization .......... 25

Correcting the melting layer effects on rainfall retrievals with a polarimetric vertical profile approach based on a local climatology .......... 26

Towards smarter weather radar: a simulation study of adaptive scanning strategies for improved precipitation monitoring and forecasting. .......... 27

Development and Calibration of a Low-cost AESA Module for Weather Sensing at X-band .......... 28

Estimating precipitation charcteristics using disdrometer and RADAR observations .... 29

Ice particle characterisation with the VISSS: insights from field campaigns and statistical analysis .......... 30

Introducing the maximum diameter as a new 2DVD variable for the investigation of aerosol-cloud-interaction .......... 31

GPM-API: A Python Interface to Access the Global Precipitation Measurement Mission Satellites Data Archive .......... 32

Evaluation of Traditional and Innovative Methods for Reflectivity Calibration in Meteorological Radar . . . 33
Country-wide analysis of CML rainfall estimation in Zambia: Strengths, weaknesses and the way forward . . . 34
Multi-frequency radar observations of mountainous precipitation during the CHOPIN campaign . . . 35
Do crowdsourced data improve rainfall observations at the catchment scale? A Europe-wide assessment . . . 36
IcePolCKa - A Review . . . 37
Enhanced composition of X- and C-band radar data . . . 39
Flux Observations for Process-Informed Quantitative Precipitation Estimates . . . 40
The Vertical Distribution of Particle Shape (VDPS) Method: Introduction, Application and Evaluation . . . 41

**Session 1.B: From classical to integrated remote sensing. New retrieval and estimation techniques (e.g. fusion, Bayesian) . . . 42**

A probabilistic AI-based merging of Commercial Microwave Link and Radar QPE . . . 43
Hydrometeor classification based on cloud radar Doppler spectrum peaks using the PEAKO-peakTree toolkit . . . 44
Investigating the Origin of W-Band Radar KDP Signatures Inside and Below the Dendritic Growth Layer . . . 45
Processing of Doppler spectra collected by an airborne cloud radar . . . 46
Quantifying Riming by Combining the Video In Situ Snowfall Sensor with Cloud Radar Observations . . . 47
Impact of seeder-feeder cloud interaction on precipitation formation over the Swiss plateau: a case study and statistics based on extensive remote-sensing, in situ and model data . . . 48
The role of rain evaporation for the energy and radiation budget of the trades . . . 50
Exploring Total Column Water Vapor retrievals from Satellite-Based Near-Infrared Measurements in Pre-Convective Environments . . . 51
Wind drift effect on radar data through analysis of individual drop trajectories using 3D+1 innovative wind product . . . 52
Melting Layer and Riming Detection from Vertically Pointing C-band Radar Observations . . . 53
Hydrometeor partitioning ratios for polarimetric ground-based and dual-frequency space-borne and radar observations . . . 54
Developement of a microphyscial retrieval based on beam-aware columnar vertical profiles: Combining side-looking polarimetry with vertical radar measurements . . . 55
What can radars tell us about snowfall microphysics? Insights from a MCMC framework 56
Addressing QPE Limitations with Solid State Transmitter X-Band Radar . . . 57
Data-driven classification of polarised weather radar observations . . . 58
The GPM-GEO Archive: A Multimodal Remote Sensing Dataset for Cloud and Precipitation Research . . . 59
Non-parametric Estimation of Drop-Size Distribution Profiles Using Cloud Radar Spectral Polarimetry . . . 60

Maximum-Likelihood and Hamiltonian Monte Carlo Techniques to Doppler Moment Estimation for Precipitation using Weather Radar Echoes . . . 61

**Session 2.A: Enhancing process understanding. New observations for modeling and parameterization development . . . 62**

A statistical evaluation of cloud microphysics schemes in a numerical weather prediction model with polarimetric radar observations . . . 63

Comparing raindrop size distributions from the two-moment microphysics scheme of the ICON-RUC model with disdrometer observations . . . 64

How important is turbulence for the formation of snow aggregation and riming in Arctic clouds? . . . 65

A detailed climatology of quasi-vertical profiles (QVPs) under stratiform conditions with identification and analysis of different microphysical processes (MPPs) . . . 66

Laboratory studies upon the fragmentation of ice particles due to collision . . . 67

The relationship between cloud thermodynamic structure and the properties of precipitation from cloud radar and disdrometer observations . . . 68

ROTOЯ - Constraining the role of warm rain processes for cloud amount and cloud organization in the trades . . . 69

Ground-Based Observations of Secondary Ice Production: A Case Study Showing Droplet Fragmentation during Refreezing Rain . . . 70

DISDRODB: a global data base of raindrop size distribution observations . . . 71

Linking Ice-Phase Microphysics to Raindrop Characteristics, and Extreme Rainfall in a Deep Convection Event in Eastern China . . . 72

Study on Microphysics of Stratiform Precipitation Based on Dual-Polarization Radar and Airborne Observations . . . 73

Can ice-ice fragmentation explain the typical radar signatures in the dendritic growth layer? An investigation combining polarimetric multi-frequency radar observations wth Lagrangian Monte-Carlo particle modeling . . . 74

From Cloud Tops to Surface: Statistical Insights into Stratiform Microphysics over Germany and Türkiye . . . 75

Detailed spectral-bin microphysics simulations of primary ice formation in artificially seeded supercooled stratus clouds . . . 76

Investigation of aerosol effects on precipitation initiation processes in the alternately clean and aerosol-laden environment of New Zealand Aotearoa . . . 78

Lack of INP and precipitation in supercooled stratus clouds over the Swiss Plateau might be explained by upwind INP activation and removal . . . 79

Quantifying the Underestimation of Rainfall by Rain Gauge Networks: Significance, Implications and Recommendations . . . 80

Development and Assessment of Instruments for Rainfall Microphysics Observations . . . 81

**Session 2.B: Enhancing process understanding. Model parameter estimation . . . 82**

Exploiting polarimetric radar observations to improve the ICON-D2 2-moment microphyiscs . . . 83

Predicting Realistic Snow Shape for Improved Polarimetric Radar Simulations . . . 84

On the geometry and growth of aggregate snowflakes . . . 85

A gravity-driven inverse cascade controls the size distribution of raindrops . . . 86

Simulation of convective precipitation in idealized and realistic supercell cases with the P3 cloud microphysics scheme in ICON ........ 87
Preparing the two-moment microphysical scheme for operational forecasts using radar and satellites ........ 88
Towards Evaluating Microphysical Pathways Of Midlatitude Snow Formation in the ICON Model ........ 89
**Session 3.A: Prediction scales and model development. Modeling elements in nowcasting ........ 90**
Application of a predictive recurrent neural network for quantitative precipitation nowcasting ........ 91
Enhancing radar-based nowcasting of heavy precipitation using IoT Rain Sensors and Machine Learning: A Field Study in Four German Cities ........ 92
Localized Radar-Based Nowcasting of Convective Rainfall ........ 93
Nowcasting model of thunderstorms intensity and probability TSP ........ 94
Advanced Heavy Rain Forecasting: Artificial Intelligence-Driven Insights from High-Density Optical Rain Sensor Networks ........ 95
**Session 3.B: Prediction scales and model development. Hectometer scale modeling for precipitation ........ 96**
Studies of Convection-Permitting Ensemble Forecasting for ICON-D2 with a 1km Nest over the Alps ........ 97
**Session 4.A: Seamless prediction. Data assimilation integrating nowcasting and new observations ........ 98**
Assimilation of Lightning and Reflectivity Texture Fraction in ICON-LAM ........ 99
Assimilation of 3D polarimetric microphysical retrievals using the operational ICON model framework of DWD ........ 100
Commercial Microwave Link (CML) Data Assimilation with the LETKF ........ 101
Evaluate the Impact of Dual-Polarization Radar Data Assimilation Using Observation Operators ........ 102
Latest Result of Including ZDR Column for Enhanced Radar Data Assimilation at German weather Service (DWD) ........ 103
High resolution data assimilation in the GLORI Project ........ 104
Using a 3D Wind retrieval algorithm to improve the understanding of dynamics of hail cells in Germany ........ 105
Optimal exploitation of polarimetry for precipitation-induced flood forecast ........ 106
**Session 4.B: Seamless prediction. Blending and probabilistic techniques based on nowcasting and NWP ensembles ........ 107**
Current status of SINFONY – The combination of nowcasting and numerical weather prediction for forecasting convective events at DWD ........ 108
Project IMA: seamless predictions at the Royal Meteorological Institute of Belgium ........ 109
Seamless Combination of Object-Based Probabilistic Nowcasting and NWP Ensemble of Convective Cells From KONRAD3D ........ 110
Seamless Integrated Rainfall Forecasts using Nowcasting and NWP-Ensembles ........ 111

Scale-Dependent Evaluation of Seamless Short-Term Forecasts of Convective Precipitation ... 112
Verification and further development of KONRAD3D-SINFONY ... 113
**Session 5.A: Precipitation and hydrological models. Extreme precipitation events ... 114**
Revealing the Structure of Precipitation Extremes: a spatio-temporal Wavelet Approach 115
Simulating intra-event return period co-occurrences in short-duration intense precipitation events ... 116
Extreme rainfall over West Africa: Current state and projected impacts of climate change 117
Comprehending Meteorological Drought in the Tons River Basin, India: A Spatio-Temporal Assessment of Variability and its impact on water resources ... 118
Prognostic ParFlow Integrated Hydrologic Model Applications at Stakeholder Scale Over Central Europe ... 119
GSDR: A global sub-daily rainfall dataset for understanding extreme precipitation ... 120
Hybrid modelling setups for real-time urban pluvial flood mapping ... 121
Evaluating the performance of X-band radars for QPE during heavy rain events in western Germany ... 122
Precipitation forecast enhancements in Destination Earth: advancing toward km-scale Global simulations ... 123
The Southern German flooding in May and June 2024 ... 124
Return Period Analysis of Maximum Daily Rainfall Disasters in the Zagros Mountains, Iran: March (2019) ... 125
A globally-applicable conceptual model for extreme precipitation events ... 126
Urban influences on convective rainfall across different city structures ... 127
Real-time assessment of rainfall extremity using observations and seamless short-term forecasts in small river catchments in Germany ... 128
Tailoring Weather Warnings in the DWD Warning Portal to Meet the Requirements of Flood Forecasting Centers ... 129
Precipitation and hydrological events in Northwest Bulgaria since 2001 ... 130
Automatic Early warning for severe thunderstorms in Piemonte, Italy ... 131
**Session 5.B: Precipitation and hydrological models. Evaluation, verification and interfaces ... 132**
Operational Hydrologic Ensemble Forecasts in Small Catchments – Implementing New Products for Precipitation Estimation and Seamless Predictions ... 133
Evaluation of precipitation products' characteristics over Germany for hydrologic model forecasts ... 134
DeepWaive: A Paradigm Shift in Flood Forecasting through a Hybrid AI Foundation Model ... 135
Development of Flood Level Prediction Model for Hangang Jamsoo Bridge Using Weather Climate Data and Artificial Neural Networks ... 136
Tailoring SINFONY forecasts and other DWD products to flood forecasting applications following a co-design approach ... 137
Developing early warning systems for Greek Prefectures and Municipalities ... 139

Predictability plots as a means to assess meteorological input for hydrological models . . 140
Predicting hydrological drought in Gangwon the Far East using weather climate data and AI models . . . . . . . . . . 141
Predicting inflows to the Soyang River Dam using Weather climate data and Machine learning . . . . . . . . . . 142
QPE, QPF and EPS in flood forecasting . . . . . . . . . . 143
Rain, Snow or Freezing Rain? – Radar-based Surface Precipitation Type Analysis and Verification at DWD . . . . . . . . . . 144
Initial Results of Implementing SINFONY Forecast Products in Flood Prediction Using the LARSIM Model at the Flood Forecast Centre of Baden-Württemberg . . . . . . . . . . 145
Improving Flood Forecasting by Assimilating Remotely Sensed Soil Moisture Data into the ParFlow-CLM Model . . . . . . . . . . 146
Operational High-Resolution Hydrological Forecasting Systems for Short-to-Sub-Seasonal Predictions in Germany . . . . . . . . . . 147

# Keynotes

### The amazing journey through an opportunistic satellite sensing system: from the 'bad-looking' raw data to the 'handsome' precipitation estimate

1) Filippo Giannetti* (University of Pisa)

Opportunistic sensing is an unconventional approach to data collection in practical applications such as environmental monitoring, weather forecast, climatology, surveillance, etc., which uses devices that are not purposely dedicated to this task. In the last 15 years, opportunistic sensing gained a steadily increasing attention by researchers and nowadays a broad and solid literature is available on this topic. In particular, the opportunistic use of pre-existing microwave links, either terrestrial or satellite, emerged as an effective and promising technique for inferring accurate real-time estimates of precipitation intensity from the measurement of signal attenuation at the receiver site. Furthermore, the opportunistic use of signals received by ground terminals of satellite services users/subscribers, mainly TV broadcasting (but also broadband access and IoT), revealed to be particularly appealing due to the low-cost and the ease of deployment of the receiving devices, which are acting as sensors. To this respect, this tutorial contribution is aimed at: (1) illustrating, step by step, the data processing chain of a satellite-based opportunistic rain sensing system, from the measurement of the received satellite signal strength (briefly addressed to as "raw data") to the estimation of the precipitation intensity; (2) addressing the disturbances affecting collection of the data and the technical challenges involved in their processing; (3) identifying the key performance indicators to assess the accuracy of opportunistic estimates against measurements collected by conventional sensors, such as rain gauges or radars;(4) illustrating some practical case studies and outlining some future perspectives.

#### Acknowledgements

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## Flood forecasting in Bavaria: Organization of the flood information service (HND) and limits of early warning due to model uncertainties discussed on the basis of examples from the 2024 flood event in Swabia

1) Natalie Stahl-van Rooijen* (Bavarian Environmental Agency), 2) Nicolas Dalla Valle (Bavarian Environmental Agency), 3) Joachim Stoermer (Bavarian Environmental Agency)

Flood protection and flood prevention are of fundamental importance for all settlements near bodies of water. Climate change is accelerating extreme precipitation and thus also increasing the importance of flood prevention. A central element of this is flood forecasting, as this is what makes many precautionary measures possible in the first place. In Bavaria, the flood forecasting centers continuously simulate the water balance area-wide and use this as a basis to create discharge forecasts for more than 200 gauging stations. These forecasts form the operational basis for flood risk prevention.

This contribution explains how the flood information service (HND) is organized and carried out in Bavaria. In addition, the uncertainty and quality of the water balance modeling and the resulting discharge forecasts for the 2024 flood event are discussed against the background of the precipitation forecasts.

The floods of May/June 2024, which caused extreme discharges and flooding along the southern tributaries of the Danube in Swabia and Upper Bavaria in particular, were not concentrated on the edge of the Alps, as was the case with previous major floods (1999, 2005, 2013), but downstream to the north. There, smaller streams and lateral tributaries contributed significantly to the catastrophic damage in populated areas. The event also revealed the limits of gauge-based predictions, as some gauges were bypassed by significant portions of the discharge.

Due to meteorological forecasts, a major event was already recognizable some time in advance and a general operational readiness for the HND in Bavaria was communicated on 29.05.2024, two days before the first warning thresholds were reached. However, the later focus on Swabia based on the forecasts first materialized on 30.05. to 31.05.2024. But for a long time even the ensemble forecasts had not depicted the extension to catchment areas further east as a scenario. For this reason, there was also criticism of the forecasts, especially for the Paar (Danube tributary), Glonn and Amper (western Isar catchment area).

Overall, the new ensemble products are very useful for estimating the potential severity of forecast weather conditions and are increasingly being used in the flood information service. However, the early warning of specific catchment areas remains difficult, especially in the case of extreme precipitation, as the location of precipitation is still subject to great uncertainty and a few kilometers offset makes a big practical difference for hazard prevention in small catchment areas. This is shown using the example of the Paar river.

## On the importance of precipitation datasets for operational hydrological monitoring and forecasting

1) Christel Prudhomme* (European Centre for Medium-Range Weather Forecasts (ECMWF)), 2) Ervin Zsoter (European Centre for Medium-Range Weather Forecasts (ECMWF)), 3) Cinzia Mazzetti (European Centre for Medium-Range Weather Forecasts (ECMWF)), 4) Maliko Tanguy (European Centre for Medium-Range Weather Forecasts (ECMWF)), 5) Jasper Denissen (European Centre for Medium-Range Weather Forecasts (ECMWF)), 6) Gwyneth Matthews (European Centre for Medium-Range Weather Forecasts (ECMWF)), 7) Christoph Rudiger (European Centre for Medium-Range Weather Forecasts (ECMWF)), 8) Peter Salamon (Joint Research Centre), 9) Estibaliz Gascon (European Centre for Medium-Range Weather Forecasts (ECMWF)), 10) Nikos Mastrantonas (European Centre for Medium-Range Weather Forecasts (ECMWF)), 11) Patricia de Rosnay (European Centre for Medium-Range Weather Forecasts (ECMWF))

Some of the most damaging natural disasters are hydrological extremes, with terrible consequences on human life, infrastructure, and the environment, such as the flash floods that devastated the Valencia region of Spain in October 2024. Understanding the variability and patterns in hydrological extremes and being able to anticipate events are essential to increase society's resilience and preparedness, especially important in the context of global warming.
River discharge modelling is an invaluable tool to help understand and predict such events. Models complement in-situ river discharge observations. This capability is particularly critical in poorly gauged regions, where traditional observation networks may be sparse or non-existent and in small catchments where short concentration times make it impossible to rely on river discharge observations to issue time-effective warnings.
As a key driver of river discharge, precipitation plays a key role in hydrological modelling and forecasting. This talk will go through how precipitation data can be used in hydrological monitoring and forecasting, from hydrological model calibration and set-up of reference datasets and extreme event catalogues of the past, to near real-time monitoring of hydrological status and forecasting at horizons from hours to months. Drawing from examples from the European and Global Flood Forecasting Systems EFAS and GloFAS, two operational early warning systems of the Copernicus Emergency Management Service of the European Commission, we will show some of the requirements and limitations but also potential for application and improvement of different precipitation datasets and products used at continental and global scales.

### Flash floods predictions and mitigation under change – challenges, models, perspectives

1) Erwin Zehe* (Institute of Water and Environment, Karlsruhe Institute of Technology), 2) Franziska Villinger (Institute of Water and Environment, Karlsruhe Institute of Technology), 3) Ralf Loritz (Institute of Water and Environment, Karlsruhe Institute of Technology), 4) Ashish Manoj J (Institute of Water and Environment, Karlsruhe Institute of Technology), 5) Judith Nijzink (Environmental Sensing and Modelling, Luxembourg Institute of Science and Technology), 6) Laurent Pfister (Environmental Sensing and Modelling, Luxembourg Institute of Science and Technology)

Flash flood are among the most dangerous natural hazard - the flash flood series in 2016 caused about Euro2.5 bn of economic losses in Southern Germany alone. Flash floods occur in small catchments or on individual hillslopes within a span of minutes to hours in response to high-intensity convective rainstorms, resulting in strong infiltration excess and significant overland flow. Extreme overland flow often mobilizes large amounts of sediments, leading onsite to loss of fertile land, while their deposition in settlements and reservoirs is causing huge damages. Suspended particles may, furthermore, carry substantial amounts of contaminants, heavy metals, pathogens) and nutrients, impacting the quality of surface water bodies.
A warmer climate will due to Clausius-Clapeyron scaling likely lead to increasing frequencies of more intense rainstorms triggering more frequent flash flood and erosion events. This is worry-some because predictions of flash floods formation is due to the threshold nature of infiltration excess overland flow a great challenge to today's forecasting systems. Flash floods are, furthermore, rarely observed with conventional rain and stream gauge networks. The sample for statistical learning and training of AI-based models is thus small.
Here we will revisit the cascading processes and thresholds controlling coupled water and sediment fluxes during convective rainstorms, and elaborate on the related challenges for standard hydrological forecasting systems. We will in particular show that the current practice of separating hydrological and hydraulic simulations is largely inappropriate, as changes in the overland flow mass balance affect it's velocity and vice versa. We then provide evidence that gradient-resolving physics based models account for this strong coupling of the mass and momentum balance during successful predictions of historical flash floods. They are, furthermore, most helpful for quantifying the sensitivity of flash flood runoff to changes in precipitation intensity as well as soil and land use characteristics. We show that the latter is key for developing integrated flood safety concepts, combining distributed land use measures dampening infiltration excess runoff, with central flood defense reservoirs.
We finally show that physics based models can be used for operational flash flood warnings in head water catchments, using re-analysis products as input and the inverted mass balance of flood defense reservoirs as target. This opens opportunities for using data from several hundred of flood defense reservoirs for learning.

## Advancing Precipitation Estimation and Prediction through Deep Learning at Météo-France

1) Léa Berthomier* (Météo-France AI Lab), 2) Frank Guibert (Météo-France AI Lab), 3) Bruno Pradel (Météo-France AI Lab), 4) Théo Tournier (Météo-France AI Lab)

This presentation will showcase three innovative projects developed at Météo-France's Artificial Intelligence Laboratory, aimed at improving precipitation estimation and prediction using state-of-the-art deep learning techniques.

The first project, Espresso, focuses on satellite-based precipitation estimation. Leveraging deep learning, Espresso enables accurate retrieval of precipitation by integrating multispectral satellite data and high-resolution ground truth. This product, developed jointly with Météo-France's Operations department, is now used daily by forecasters in overseas territories that are not covered by radar.

The second project explores short-term precipitation forecasting using Google DeepMind's DGMR model. By adapting this generative approach to Météo-France's operational context, we aim to provide rapid and reliable precipitation nowcasts, crucial for extreme weather events. This project is currently under evaluation by our Operations department.

Finally, I will discuss our medium-range forecasting project, which employs a deep learning model designed to emulate Météo-France's high-resolution AROME model. This research project, under development in collaboration with the French National Research Center for Meteorology, trains a deep neural network on 20 parameters of AROME analyses to make 1-hour timestep forecasts. The model can then be applied to generate forecasts of any length in just a few seconds. This method could reduce computational costs while maintaining competitive accuracy, offering a promising alternative for medium-term precipitation forecasting.

These projects underline the potential of AI to revolutionize meteorological practices, balancing computational efficiency with prediction accuracy.

## Precipitation nowcasting: from Lagrangian models to advanced ML approaches

1) Ulrich Hamann* (MeteoSwiss), 2) Ioannis Sideris (MeteoSwiss), 3) Loris Foresti (MeteoSwiss), 4) Daniele Nerini (MeteoSwiss), 5) Jussi Leinonen (NVIDIA Corporation), 6) Athanasios Ntoumos (MeteoSwiss), 7) Urs Germann (MeteoSwiss)

Precipitation nowcasting is the task of predicting rainfall over very short time scales (from a few minutes to a few hours), particularly important for applications in flood management, aviation, and emergency response. Unlike traditional weather models that rely on longer-term atmospheric dynamics, nowcasting focuses on extrapolating current weather observations, such as radar data, to provide highly localized and timely forecasts. The accuracy of such predictions is crucial for mitigating the impacts of severe weather events like flash floods, regional flooding, and intense thunderstorms.

A simple yet effective method to perform precipitation nowcasting is the Lagrangian model, where the precipitation features are followed along their trajectories, assuming their movement is governed by the prevailing winds. This approach can be enhanced by estimating the increase or decrease of precipitation intensity e.g., to describe convective growth or orographic blockage. A common approach is to apply regression techniques to relate the historical behavior of rainfall intensification to various factors such as temperature, humidity, or wind patterns. Alternatively, precipitation tendencies could be extracted from NWP forecasts.

Just as any other forecasting technique, the skill of precipitation nowcasting was found to depend on multiple factors such as the meteorological conditions, geographical location, spatial and temporal scales. Hence, the nowcasting community rapidly acknowledged the importance of estimating predictive uncertainty. A common approach is based on stochastic simulation, in which correlated noise fields are used to perturb a deterministic nowcast. Substantial research efforts have been made to make the perturbation fields as realistic as possible and consistent with the nowcast uncertainty. An alternative approach is to apply generative ML models such as GANs or diffusion models to create realistic spatio-temporal structures.

In the outlook we describe the integration of precipitation nowcasting and forecasting into a unified discipline. Machine learning models are capable of handling both large-scale and fine-grained temporal and spatial data. Hence, the same methodologies and architectures can now seamlessly support both forecast horizons.

### How ML is transforming our approach to seamless weather forecasting

1) Daniele Nerini* (MeteoSwiss), 2) MeteoSwiss colleagues

Seamless forecasting is an important paradigm in operational weather prediction, aimed at delivering consistent and actionable forecasts across temporal and spatial scales. Traditionally, achieving this vision relies on a combination of diverse strategies such as data assimilation, rapid update cycles, heuristic nowcasting techniques, blending schemes, and statistical postprocessing. While these approaches have often produced valuable results in practice, they also exposed fundamental limitations in achieving true seamlessness. Moreover, these solutions can be resource-intensive, both in computational cost and maintenance effort, placing a considerable burden on operational weather services.
The emergence of machine learning (ML) methods presents a powerful opportunity to overcome such limitations and break down traditional silos in weather prediction. Neural networks, with their capacity to model complex non-linear relationships and efficiently handle high-dimensional data, are particularly well-suited to serve as a unifying forecasting framework spanning nowcasting to extended range. Once trained, these models run orders of magnitude faster than traditional numerical models and integrate heterogeneous observational and model data, enhancing forecast accuracy while enabling seamless transitions across forecast time scales.
This talk will present and discuss the strategies driving seamless forecasting at MeteoSwiss, with a particular focus on innovations in ML-based frameworks and their role in achieving scalable, operationally sustainable, and truly seamless weather prediction.

### Nowcasting extreme rainfall over the UK

1) Katie Norman* (Met Office), 2) Matt Clark (Met Office), 3) Ed Pavelin (Met Office), 4) Andrew McNaughton (Met Office), 5) Anna Booton (Met Office), 6) Billie Mackenzie (Met Office), 7) Graeme Kelly (Met Office)

4.6 million properties in England are at risk of surface water flooding according to recent analysis from the Environment Agency in England. The Met Office is seeking to improve its warnings for short duration, high intensity rainfall to help the public better prepare for and respond to such severe weather. Whilst the possibility of extreme rainfall somewhere in the UK is often predicted several hours or more ahead, it is often not with sufficient confidence in the location of the most intense rainfall to escalate a warning. Current Numerical Weather Prediction (NWP) provides skilful forecasts out to several days ahead, but this comes at the expense of its skill at very short lead times.
To address these shortcomings, the Met Office are developing a nowcasting system named PLUVIA to support Operational Meteorologists in issuing warnings and guidance for severe weather, in particular that associated with deep moist convection (DMC). PLUVIA provides a near-surface analysis (Mesoanalysis) using crowd-sourced observations, which draws more closely to observations than the analysis from NWP, to better support the situational awareness of Operational Meteorologists. The PLUVIA Cell Tracker uses 3D radar observations to monitor and forecast the trajectory of the rainfall cores associated with DMC.
This presentation will describe PLUVIA and how it is used by Operational Meteorologists and Hydrometeorologists at the Met Office and Flood Forecasting Centre to issue National Severe Weather Warnings and Rapid Flood Guidance.

## Making use of supplementary observations for the development of physical parameterizations

1) Linda Schlemmer* (Deutscher Wetterdienst), 2) Maike Ahlgrimm (Deutscher Wetterdienst), 3) Sophie Löbel (Deutscher Wetterdienst), 4) Alberto de Lozar (Deutscher Wetterdienst)

The performance of numerical weather prediction (NWP) systems is typically evaluated using standard verification. While this is an essential procedure to ensure the quality of operational forecasts, it is equally important to harvest additional observations for the evaluation of simulations. These supplementary observations are needed to study the underlying physical processes in detail and to enable future development of physical parametrizations.
Hereby, a combination of more established observational products and new observations that have for example been collected during field campaigns can be very beneficial. The way is illustrated in which spatially dense observations collected during the FESSTVaL campaign in combination with Doppler LiDARs have been used to gain a deeper understanding of boundary-layer processes. Moreover, the role of drag processes during the Perdigao field campaign is depicted. In addition, the benefit of combinations of instruments to assess the performance of a model is shown. The range of ICON simulations thereby span scales from global nwp down to high-resolution hectometer-scale limited area setups.
Based on the comparison of the different models to observations for example insights are gained on the partitioning between liquid water and ice within modelled clouds, or the importance of the subgrid-scale orographic drag scheme, even at high resolutions, is demonstrated.

## Session 1.A: From classical to integrated remote sensing. New observation strategies for clouds and precipitation (multi-frequency, spectral polarimetry, multi-sensor)

**ID: 107, Oral Presentation**

## Weather radar adjustment with pyRADMAN: Experiments with and without commercial microwave links

1) Maximilian Graf* (Deutscher Wetterdienst), 2) Christian Chwala (KIT (IMK-IFU)), 3) Matthias Gottschalk (Deutscher Wetterdienst), 4) Malte Wenzel (Deutscher Wetterdienst), 5) Tanja Winterrath (Deutscher Wetterdienst), 6) Julius Polz (KIT (IMK-IFU))

Data from commercial microwave links (CMLs) have proven to provide useful rainfall estimates. With their extensive numbers, potential for real-time data availability, and measurement near the ground, they offer the potential to adjust weather radar data, similar to the operational use of rain gauges by national meteorological services (NMS). Furthermore, CMLs offer a path-averaged rainfall estimate that resembles the areal measurements obtained from weather radars more closely than the point measurements from rain gauges. However, several challenges hinder the use of CML data for radar within the operational setting of NMS. These include the (real-time) acquisition of CML data from mobile network operators, the uncertainties related to their rainfall estimation and the question how to actually merge gridded data with their path-averaged information. In the HoWa-PRO project, we have established a CML data stream from Ericsson to the German Weather Service (DWD) and developed the Python framework pyRADMAN to merge radar, rain gauge and CML data in real-time. In this contribution, we will present pyRADMAN and its resulting rainfall products. The methodology in pyRADMAN builds on the adjustment technique from the operational software RADOLAN, using refined methods for CMLs. Additionally, we tested other adjustments like kriging with external drift and conditional merging, used classic advection correction or the deep-learning model ResRadNet to correct the radar prior to the adjustment and increased the temporal resolution of adjusted products to up to 15 minutes. pyRADMAN enables modular implementation and testing of new pre-processing and adjustment methods, supporting future collaborative efforts.

**ID: 29, Oral Presentation**

## Tropical rainfall nowcasting with Commercial Microwave Links: opportunities and current limitations

1) Bas Walraven* (Delft University of Technology), 2) Ruben Imhoff (Deltares), 3) Aart Overeem (Royal Netherlands Meteorological Institute), 4) Miriam Coenders (Delft University of Technology), 5) Rolf Hut (Delft University of Technology), 6) Luuk van der Valk (Delft University of Technology), 7) Remko Uijlenhoet (Delft University of Technology)

Accurate and timely precipitation forecasts are crucial for flood early warnings and mitigating other rainfall-induced natural hazards like landslides. For forecasts up to three hours ahead, rainfall nowcasts are increasingly being used. Generally, these nowcasts statistically extrapolate real-time remotely sensed quantitative precipitation estimates, often based on weather radars. However, the global distribution of high-resolution (gauge-adjusted, ground-based) weather radar products is heavily skewed, largely favoring Europe, Northern America, and parts of East Asia. In many low- and middle-income countries, predominantly located in the tropics, weather radars are largely unavailable due to high installation and maintenance costs, and rain gauges are often scarce, poorly maintained, or not available in (near) real-time.

A viable and 'opportunistic' source of high-resolution space-time rainfall estimates is based on the rain-induced signal attenuation experienced by commercial microwave links (CMLs) in cellular communication networks. Based on received signal power levels, path-averaged rainfall intensities can be estimated, and then interpolated to produce high-resolution rainfall maps. In this study, we explore the opportunities and limitations that arise from using only CML-based rainfall estimates for rainfall nowcasting in Sri Lanka.

Using 12 months of data from 2019 and 2020 from a Sri Lankan CML network that predominantly covers the northern half of the country, we create spatial rainfall fields at 15-minute intervals. With the nowcasting algorithm pySTEPS, probabilistic nowcasts are created for lead times up to three hours for events with different durations ranging from 1 to 24 hours. The nowcasts (QPF) are evaluated against the CML rainfall fields (QPE) across 12 catchments of varying sizes and with varying CML coverage and density. The results are further analyzed by season to determine the potential influence of rainfall intensity and dominant wind direction on the nowcasts' accuracy. Hourly rain gauges, where available, are used as an independent (point) reference source of rainfall information.

With this novel application of CML-derived rainfall fields, essentially providing a 'weather radar' in the tropics, we identify the major sources of uncertainty in the nowcasts and highlight the potential impact of relying solely on CMLs for operational early warning services in regions that lack dedicated rainfall sensors.

**ID: 83, Oral Presentation**

### Urban surveillance camera for urban extreme rainfall estimation

1) Xing Wang* (Nanjing University), 2) Kun Zhao (Nanjing University), 3) Hao Huang (Nanjing University)

In recent years, under the dual influence of global warming and urbanization, extreme precipitation events in cities have become more frequent. The randomness, suddenness, and spatiotemporal variability of urban precipitation have significantly increased, posing serious threats to the healthy development of society and the safety of people's lives and property. High spatiotemporal resolution surface precipitation observations are crucial for meteorological forecasting, climate analysis, and disaster warning. The widely distributed urban surveillance cameras can continuously record precipitation events and dynamically describe changes in rainfall intensity, offering advantages such as high density, rapid speed, and low cost. This provides a new opportunity for a high-resolution perception of urban precipitation. To this end, this study analyzes the imaging patterns of heavy rainfall from the novel perspective of urban surveillance videos. It establishes a dynamic model for the relationship between precipitation intensity and video features. Based on this, a deep learning-based algorithm for quantitative estimation of precipitation from surveillance videos is proposed, and long-term precipitation observation experiments are conducted in various locations, including Nanjing, Wuxi, Changzhou, and Vienna. Comparison with synchronous measurements from devices like 2-DVD and Parsivel shows that in heavy rainfall scenarios with intensities ranging from 20 mm/h to 90 mm/h, the surveillance cameras achieve 75% accuracy in estimating rainfall intensity and 83% accuracy in measuring cumulative rainfall. In scenarios with rainfall intensities from 90 mm/h to 140 mm/h, the surveillance cameras can achieve 70% accuracy in measuring precipitation intensity and 78% accuracy in cumulative rainfall measurements. This research aims to enhance the quantitative estimation accuracy of precipitation using surveillance cameras, thereby providing a beneficial supplement to improve the high-resolution perception capability of urban heavy rainfall and offering foundational data support for the forecasting and analysis of urban precipitation.

**ID: 105, Oral Presentation**

## Achievments of the COST Action on Opportunistic Precipitation Sensing (OpenSense)

1) Christian Chwala* (KIT (IMK-IFU)), 2) Vojtěch Bareš (Czech Technical University in Prague), 3) Hagit Messer (Tel Aviv University), 4) Roberto Nebuloni (Consiglio Nazionale delle Ricerche (CNR)), 5) Martin Fencl (Czech Technical University in Prague), 6) Aart Overeem (Royal Netherlands Meteorological Institute), 7) Maximilian Graf (Deutscher Wetterdienst), 8) Remco van de Beek (SMHI, Sweden), 9) Jonas Olsson (SMHI, Sweden), 10) Laura Varga (Budapest University of Technology and Economics), 11) Cristina Deida (Vrije Universiteit Brussel), 12) Jonatan Ostrometzky (Tel Aviv University), 13) Luis Angel Espinosa (Association of Instituto Superior Técnico for Research and Development, Lisbon), 14) Natalia Hanna (TU Wien), 15) Remko Uijlenhoet (Delft University of Technology)

The COST Action OpenSense (https://opensenseaction.eu) focuses on opportunistic sensing (OS) of precipitation using data from commercial microwave links (CML), satellite microwave links (SML) and personal weather stations (PWS). OpenSense brings together scientists, experts from national weather services, owners of sensor networks, and end-users of rainfall products. The main goals of OpenSense are, to improve the access to country-wide and continental-scale OS data, to establish OS data as a widely acknowledged data source capable of providing reliable operational rainfall data, and to facilitate the use of the OS data for weather and hydrological forecasts. OpenSense has been active since the year 2022 and currently has more than 140 participants.
Here we present the main achievements of OpenSense and its working groups. We will highlight the large datasets that have been curated and made openly available in a standardized format. We will introduce the software ecosystem which was developed to simplify and standardize how CML, SML and PWS data are being processed and evaluated. In addition we will show examples of OS data merging and application of OS rainfall products. Finally an outlook will be given on the activities of OpenSense which aim to facilitate OS data access and operational usage on a global scale, with a particular focus to bring OS rainfall estimation to regions where traditional observation networks are sparse.

**ID: 59, Oral Presentation**

## Rainfall estimation over the San Francisco Bay Area: a new system to infuse microphysical information into QPE

1) V. Chandrasekar (Colorado State University), 2) Renzo Bechini* (Colorado State University, Arpa Piemonte), 3) Sounak Biswas (Colorado State University), 4) Robert Cifelli (University of Oklahoma)

Accurate rainfall estimation in regions with complex terrain, such as the San Francisco Bay Area, poses unique challenges. This region, like much of the western United States, is strongly influenced by atmospheric rivers (ARs), narrow corridors of intense water vapor transport that significantly impact coastal and mountainous regions. The present-day routine Z-R estimation is inadequate to capture the microphysics in ARs and hence results in inaccurate quantitative precipitation estimation (QPE). The Advanced Quantitative Precipitation Information (AQPI) system, a regional initiative, employs enhanced weather radar technology to track AR-associated precipitation with high precision, with a key goal of recording microphysical features. The AQPI system supplements the large-scale coverage of the WSR-88D network with additional, locally deployed X-band and C-band radars, enhancing the accuracy of weather monitoring, forecasting, and emergency response across the Bay Area.

This study utilizes the AQPI system's hybrid, multi-frequency radar network to improve rainfall estimation accuracy in this complex topographic environment. Key technical advancements in the AQPI system facilitate use of microphysical signatures into the QPE products and include networked calibration and enhanced radar visibility adjustments suited for complex terrain. Additionally, ongoing physical refinements are set to further improve rainfall accuracy. These include corrections for the Vertical Profile of Reflectivity (VPR) and tuning of the rainfall relationship based on microphysics and dual-polarization measurements, preventing contamination from ice.

These enhancements collectively aim to improve the precision of hydrological forecasting, providing critical insights for effective water resource management and flood mitigation efforts in the Bay Area.

**ID: 81, Oral Presentation**

## Deep Learning for Multimodal Precipitation Estimation: From Research to Operationalization

1) Joseph Casey (Vrije Universiteit Brussel), 2) Lesley De Cruz (Royal Meteorological Institute of Belgium, Vrije Universiteit Brussel), 3) Steven Dewitte (Royal Observatory of Belgium), 4) Arthur Moraux* (Royal Meteorological Institute of Belgium), 5) Adrian Munteanu (Vrije Universiteit Brussel)

Deep Learning (DL) has seen multiple successes in Artificial Intelligence (AI) applications, such as image and text generation, visual recognition, and speech recognition. Its popularity has grown beyond AI, with wide usage in geoscience applications like meteorology, where large datasets are available for training DL models.
At the Royal Meteorological Institute of Belgium (RMIB), we studied the application of DL for precipitation estimation, particularly to merge multiple data modalities like rain gauges, weather radars, and satellite radiometer images. A model combining these modalities offers improved coverage compared to traditional methods that rely on radar scans corrected by rain gauges. Additionally, a well-trained DL model could provide more accurate precipitation estimates.
We developed a Convolutional Neural Network (CNN) at RMIB that uses automatic rain gauge measurements, the OPERA radar composite, and infrared satellite channels of SEVIRI as inputs. The CNN employs an encoder-decoder architecture to perform a multiscale analysis of these inputs, simultaneously estimating rainfall probability and precipitation rate. The model was trained and evaluated on a dataset spanning five years (2015-2019) and covering Belgium, the Netherlands, and Germany. Our DL method was validated using an independent rain gauge dataset for both instantaneous rain detection and rain rate estimation, as well as for daily precipitation accumulation. The results showed a significant improvement over the OPERA radar composite product.
Our method is currently being developed for operationalization at RMIB and will run in near real-time. Encouraged by these results, we are also studying the application of this method to dual polarization radar variables to further enhance the accuracy of precipitation estimation.

**ID: 89, Oral Presentation**

## Correcting the melting layer effects on rainfall retrievals with a polarimetric vertical profile approach based on a local climatology

1) Raquel Evaristo* (Institute for Geosciences, Department of Meteorology, University of Bonn), 2) Julián Alberto Giles (Institute for Geosciences, Department of Meteorology, University of Bonn), 3) Ju-Yu Chen (Department of Geography, National Kaohsiung Normal University, formerly Institute for Geosciences, Department of Meteorology, University of Bonn), 4) Alexander Ryzhkov (NSSL, Norman), 5) Silke Trömel (Institute for Geosciences, Department of Meteorology, University of Bonn)

Radar-based rainfall products may suffer from strong inaccuracies due to the effect of the melting layer (ML) when the radar beam approaches the height where the temperature is 0°C. The ML is known for its enhanced reflectivity (ZH) leading to surface rainfall overestimation, but also for its decrease the cross-correlation coefficient (ρHV). To overcome this issue, methods have been developed based on the observed vertical profiles of reflectivity (VPR) which project ZH at a certain height to the surface, assuming spatially homogeneity. The method proposed here refines this approach by incorporating polarimetric variables, hence PVPR for Polarimetric Vertical Profile of Reflectivity. The model uses lookuptables generated for various ML thicknesses and heights at several elevation angles to simulate the effect of ML on the radar beam. To accurately represent the local microphysical processes, a 5-year detailed climatology of vertical profiles of polarimetric variables was generated from three C-band radars belonging to the German national meteorological service. For each radar beam, the PVPR starts by identifying the range where the bottom of the ML is reached (Hb), and the strength of the ML (S), defined by how much ρHV decreases. These two parameters are sufficient to characterize the ML. In the next step, the algorithm matches the observed values to the closest parameters in the lookuptables and applies the corresponding correction for each radial. This yields a corrected ZH field minimizing the effects of the ML and the snow beyond, which is used to calculate rain rates. Daily rainfall accumulations were validated against a dense rain gauge network, showing significant improvements compared to classical retrievals. However, some issues remain. The local climatology shows substantial variability in the parameters that define the shape of the correction, including the maximum ZH in the ML, the slope of the ZH profile in snow (β), the ML thickness, among others. To examine their impact, the parameters were modified and the PVPR applied to one month of observations. Results show that adjusting β has the largest impact, but optimal results depend on estimating its value beforehand. The effect of adjusting other parameters will also be presented and discussed.

### Acknowledgements

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**ID: 38, Oral Presentation**

## Towards smarter weather radar: a simulation study of adaptive scanning strategies for improved precipitation monitoring and forecasting.

1) Shafi Sardar* (Delft University of Technology), 2) Marc Schleiss (Delft University of Technology)

Weather radars are essential to the reliable monitoring and forecasting of intense precipitation. Yet, the current radar-based nowcasting systems often rely on sub-optimal scanning strategies which limit the system's effectiveness. Adaptive scanning techniques - where the radar's rotation speed or direction are dynamically adjusted in response to a cell's position, movement, and intensity - have the potential to significantly improve nowcasting performance. So far, these benefits have largely been assumed rather than systematically tested. In this study, we present preliminary findings from numerical simulations designed to quantify the advantages of adaptive scanning strategies for an X-band weather radar.
Our approach uses a single radar with unidirectional azimuth scanning and a variable rotation speed, targeting a single moving precipitating cell within its range. A closed-loop control system adjusts the radar's rotation speed based on real-time estimates of the cell's location and motion. We compare this adaptive scanning strategy to the conventional approach of a fixed antenna rotation speed, extending the analysis to more complex cell trajectories for greater realism. Whilst preliminary, we hope these findings will spark further research into the science of adaptive scanning and its potential to enhance precipitation monitoring, tracking, and forecasting within radar networks.

**ID: 73, Oral Presentation**

## Development and Calibration of a Low-cost AESA Module for Weather Sensing at X-band

1) Stefano Turso* (Fraunhofer FHR), 2) Rohan Mohandas (Fraunhofer FHR), 3) Carlos Galvis Salzburg (Fraunhofer FHR), 4) Thomas Bertuch (Fraunhofer FHR)

Phased Array Radars (PAR) are based on Active Electronically Scanned Array (AESA) antenna apertures enabling nearly instantaneous beam steering. Being not constrained by the inertial steering of mechanical parts, only the electronics settling time acts as a limiting factor, leading to a beam repositioning latency ranging around just a few microseconds. AESA technologies clearly bear potential to reach the goal of providing volumetric weather maps with a faster update time and therefore contribute to improving forecasting accuracy. Crucial for the actual instantiation of this technology is the development and validation of engineered solutions suitable to originate a data quality similar to their mechanically-steered counterparts while targeting reduction of ownership cost. Favorably, technological breakthroughs leading to increased functional integration on dice can finally empower electronic designs requiring a drastically reduced board surface. A compact PCB layout with a lower number of layers, tracks and parts count is an essential condition for streamlined assemblies. Additionally, inexpensive FPGAs and related COTS ICs have been found capable to generate control signals with sufficient timing accuracy and dynamic to drive the core AESA ICs like beamformers and transceivers. An AESA front-end capable of steering up to four channels, the so-called ARM (Active Row Module), has been developed to ensure actual feasibility and evaluate the achieved performance. Central for reaching the required data quality by means of cross-polarimetric discrimination in excess of 30 dB, a specialized antenna design based on feed-probe rotation has been validated. Furthermore, to ensure compliancy of the aperture radiation diagram at steering conditions (namely, sidelobe levels and similarity of beam aperture across polarizations) an automated calibration methodology has been developed to compensate for chipsets and board specific imbalances. Similarly to fully-fledged AESA implementations featuring multiple digital channels, actual radiation performance thoroughly depends on array calibration. However, while digital architectures allow for precise adjustments of the radiated power per each channel (via controlling of DACs and potentially per each radiator), the same does not hold true for single-channel analog beamformers, where analog multiport networks excite transmitting ICs and combine the received echo. Originating from the cost-compromised nature of analog beamforming architectures, an additional source of complexity therefore requires proper addressing via a calibration process relying on ICs characterization and selection of the most appropriate steering states per each hardware implementation. Initial results show suitability of properly calibrated analog beamformers for the generation of polarimetric weather products.

### Acknowledgements

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**ID: 74, Poster**

## Estimating precipitation charcteristics using disdrometer and RADAR observations

1) Nikolaos Antonoglou* (Deutscher Wetterdienst), 2) Manuel Werner (Deutscher Wetterdienst), 3) Sophie Löbel (Deutscher Wetterdienst), 4) Ulrich Blahak (Deutscher Wetterdienst)

Every precipitation event is uniquely characterised, partly due to variations in drop-size distribution that work against the correct approximation of traditional quantitative precipitation estimation (QPE). Conventional QPE techniques frequently make the glaring simplification of assuming homogeneous drop-size distributions, which can easily result in errors under varying meteorological conditions. In this work, this limitation tackled by making use of high-resolution information provided from disdrometers and enhancing QPE through the capturing of the unique microstructural features that characterize each precipitation event.
The German Weather Service (Deutscher Wetterdienst-DWD) operates a large network of 165 disdrometers all over Germany. The great dataset was a very good basis for investigations of precipitation distributions for the different German climatic regions. By applying the T-matrix methodology, we simulated radar observations, in order to derive correlations between radar moments and the three parameters of the Gamma distribution — namely, N0, mu, and lambda. The T-matrix approach provides the theoretical background necessary for a more adaptable and accurate QPE framework.
Aside from the improvement in QPE accuracy, our study allows for improvements in quality assurance (QA) processes. Accurate precipitation parameter estimation leads to more reliable attenuation correction, which is the most critical step in the QA chain. Moreover, since the DWD is currently planning to install four new X-band radar systems, the present analysis also provides a roadmap for their seamless integration in the existing C-band radar network, ensuring homogeneous generation of reflectivity maps. Until the new systems are operational, the QA for X-band was evaluating using observations of the Low-level windshear alert system (LLWAS) radars, that are also operated by the DWD.

**ID: 109, Poster**

## Ice particle characterisation with the VISSS: insights from field campaigns and statistical analysis

1) Veronika Ettrichrätz (Leipzig Institute for Meteorology (LIM), Leipzig University), 2) Nils Pfeifer (Leipzig Institute for Meteorology (LIM), Leipzig University), 3) Anton Kötsche (Leipzig Institute for Meteorology (LIM), Leipzig University), 4) Nina Maherndl (Leipzig Institute for Meteorology (LIM), Leipzig University), 5) Maximilian Maahn* (Leipzig Institute for Meteorology (LIM), Leipzig University), 6) Heike Kalesse-Los (Leipzig Institute for Meteorology (LIM), Leipzig University)

Ice particle properties, such as number, size, shape, and processes such as aggregation and riming, have a significant impact on precipitation development, cloud lifetime, and the radiative behaviour of mixed-phase and ice clouds. The variability of ice particle shapes adds complexity to cloud microphysics modelling and remote sensing retrievals. A thorough understanding of these shapes is crucial for improving the accuracy of cloud modelling, refining remote sensing retrievals, and improving climate prediction models.
To investigate ice particle properties, the Video In-Situ Snowfall Sensor (VISSS) was deployed in several field campaigns at different locations (SAIL: Gothic, Colorado; ACTRIS: Hyytiälä, Finland; PolarCAP/Cloudlab: Eriswil, Switzerland; MOSAIC: Central Arctic). The VISSS setup includes two perpendicular cameras with an illuminated background, allowing detailed video capture of hydrometeors from two perspectives. Using a supervised classification algorithm (with 1,000 labels per shape category), we analyse the particle shapes to answer following key questions What are the dominant particle shapes at each site? What is their maximum dimension and aspect ratio? How often are the particles rimed?
We highlight distinctive measurement days. For example, a measurement day from the SAIL campaign where pristine dendrites, heavily rimed dendrites and graupel occurred repeatedly, related to a low cold layer (-15°C at 2 km) and a moist, turbulent and unstable layer at 1 km. Other measurement days at Hyytiälä and Eiswil were dominated by needles, probably related to secondary ice formation or the presence of prolonged supercooled liquid stratus clouds activating biogenic ice-nucleating particles at -3 to -6°C near the cloud tops. Overall, graupel and aggregates were the most common forms at all sites.

### Acknowledgements

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**ID: 50, Poster**

### Retrieval of the maximum diameter from 2DVD observations and their synergy with remote sensing measurements

1) Tom Gaudek* (TROPOS), 2) Patric Seifert (TROPOS), 3) Cristofer Jimenez (TROPOS), 4) Kevin Ohneiser (TROPOS), 5) Andi Klamt (TROPOS), 6) Albert Ansmann (TROPOS), 7) Christopher Fuchs (ETHZ), 8) Jan Henneberger (ETHZ)

Accurate measurements of precipitation particle diameters are helpful to understand the preceding cloud processes and allow a direct evaluation of remote sensing data. In case of the two-dimensional video disdrometer (2DVD), the manufacturers software only delivers the volume-equivalent diameter as size variable. However, other ground-based in-situ sensors aim on the detection of the particle maximum diameter and also remote sensing retrievals often use the maximum diameter.
Therefore, an algorithm for deriving the particle maximum diameter $d_{max}$ from 2DVD data was developed in this study to overcome discrepancies in particle size characterization between the 2DVD, other in-situ sensors, and remote sensing retrievals. For each particle, a 2D-image is created for each of the two camera perspectives. From both images, the geometrically longest particle extent, also called Feret diameter, is calculated and the larger of the two Feret diameters is taken as $d_{max}$. 2DVD and remote sensing data from the MOSAiC Arctic Drift Experiment are used to evaluate the retrieval technique LIRAS-Ice (Lidar-Radar-Synergy-Ice) of Bühl et al. (2019) which determines ice crystal number concentrations (ICNC) and particle size information from remote sensing measurements. For this technique, a dominating particle shape has to be assumed. As the 2DVD can distinguish shapes of particles with $d_{max}$ larger than around 1 – 2 mm, depending on the particle type, also the detected shapes can be used as input for the retrieval of Bühl et al. (2019).
Results of the detection of different particle shapes using a 2DVD are shown. Furthermore, outcomes of the comparison of retrieval products and 2DVD measurements, in particular particle sizes and ICNC, are presented. The study indicates that the 2DVD is suitable to complement remote sensing measurements for the purpose of cloud microphysics investigations as it is able to detect both particle shapes and size distributions. The simultaneous operation of a 2DVD enables a better interpretation of remote sensing data and provides additional information which proved valuable for the investigation of cloud microphysical processes.

**ID: 56, Poster**

## GPM-API: A Python Interface to Access the Global Precipitation Measurement Mission Satellites Data Archive

1) Gionata Ghiggi* (EPFL), 2) Alexis Berne (Environmental remote sensing laboratory, EPFL)

The GPM-API is an open-source user-friendly Python package designed to drastically increase scientist productivity by simplifying coding tasks associated with the download, reading, manipulation, analysis and visualization of the Global Precipitation Measurement Mission (GPM) data archive.
Specifically, the software provides a seamless programming interface to (1) selectively download GPM products (2) efficiently locate these files on local storage, (3) readily access products into xarray objects for analysis (4) perform efficient on-disk and distributed data processing with Dask, (5) visualize product variables according to their specific characteristics, (6) identify precipitation events and phenomena within the dataset, and (7) extract spatial and temporal slices for the development of new retrieval algorithms or the efficient training of machine learning models.
Additionally, since remote-sensing research often involves analyzing collocated sensor measurements or retrieving time-series in a given geographic area, GPM-API provides specialized geospatial routines for on-the-fly data remapping as well as the possibility to repartition and store satellite orbits into geographically-partitioned tabular buckets. Successively, these buckets facilitate tasks such as sensor calibration and change detection, the creation of gridded temporally-aggregated products or climate data records as well as the development of next-generation retrieval algorithms with spatially varying parameters for retrospective analyses.
Finally, to streamline satellite analysis and foster research reproducibility, the software includes a mechanism for scientists to contribute their retrievals, making them readily available to the community. This also accelerate model prototyping and development and will promote new scientific discoveries.
In conclusion, by lowering the entry barrier to analyses the data, the software extends the GPM community, inviting participation from students and individuals with limited coding experience or specialized knowledge in remote sensing and meteorology. This inclusivity not only democratizes access to research and near-real-time global precipitation data but also leverages the GPM archive for broader academic and practical applications.
GPM-API is released under the permissive open source MIT license and is available at https://github.com/ghiggi/gpm_api/

**ID: 97, Poster**

## Evaluation of Traditional and Innovative Methods for Reflectivity Calibration in Meteorological Radar

1) Michael Frech (Meteorological Observatory Hohenpeißenberg, Deutscher Wetterdienst), 2) Alexander Myagkov* (Radiometer Physics GmbH), 3) Tatiana Nomokonova (Radiometer Physics GmbH)

Meteorological radar is essential for weather monitoring and forecasting, providing critical data for disaster response, resource management, and public safety. Ensuring the accuracy of reflectivity measurements is crucial for effective radar data interpretation. Continuous monitoring of reflectivity quality during radar operations is necessary to promptly detect and correct any calibration issues. This study assesses four calibration techniques. Two methods utilize rain properties from a disdrometer and a micro-rain radar to estimate expected reflectivity values, which are then compared with actual radar measurements. The discrepancy between expected and observed reflectivity serves as an indicator of calibration accuracy. The third method employs the established self-consistency approach, which uses the relationships between reflectivity, differential reflectivity, and differential phase shift. The fourth method introduces a novel technique based on drop-size distribution profiling using a W-band radar. Our analysis is based on data from a collaborative measurement campaign conducted by the German Weather Service (DWD) and Radiometer Physics GmbH. The campaign, held at the DWD meteorological observatory in Hohenpeißenberg, Germany in 2021, featured a C-band radar, disdrometer, micro-rain radar, and a scanning dual-polarimetric W-band radar over a three-month period.

**ID: 104, Poster**

## Country-wide analysis of CML rainfall estimation in Zambia: Strengths, weaknesses and the way forward

1) Nico Blettner (KIT), 2) Christian Chwala* (KIT (IMK-IFU) / Uni Augsburg), 3) Harald Kunstmann (KIT / University of Augsburg)

Rainfall estimation is challenging in data-scarce regions like Zambia. Commercial microwave links (CMLs) offer a promising solution to complement traditional data sources. We investigate the potential of CML data for hourly rainfall estimation, comparing results with satellite (IMERG) and rain gauge observations. Our analysis reveals significant variability in estimation quality, influenced by CML hardware and network characteristics. While the long CMLs in rural regions often exhibit noisy signals, the data from the dense CML network in the capital Lusaka is easier to process with the currently available methods. For the region of Lusaka we generate CML-derived rainfall maps, demonstrating the capacity to capture fine-scale rainfall patterns in an unprecedented manner for this region. For the CMLs in the rural areas, we found that information on dry and wet periods derived from geostationary satellite data can support CML processing. However, due to the considerable discrepancies between the reference datasets, the assessment of the processed CML rainfall estimates remains difficult.
In conclusion, we show that dense CML networks in African cities like Lusaka are highly useful for rainfall estimation, but for country-wide application, including the sparser network of long CMLs in rural areas, a combination with satellite data has to be investigated further. In addition, CML data access and transfer are still cumbersome to negotiate, hindering an operational real-time application.

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**ID: 110, Poster**

## Multi-frequency radar observations of mountainous precipitation during the CHOPIN campaign

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Mixed-phase clouds (MPCs), where ice crystals and snow particles coexist with supercooled liquid water droplets, affect the Earth's radiation budget significantly. Accurately representing MPCs in climate models relies on robust modelling of liquid and ice partitioning mechanisms. However, quantifying phase interactions remains challenging and is a major source of model bias. Despite increasingly sophisticated cloud microphysical schemes, discrepancies often persist between observed ice crystal concentrations and ice nucleating particles. Secondary ice production (SIP) mechanisms, which could help reduce these discrepancies, remain among the least understood and least well-parametrised aspects of MPCs.

Remote sensing instruments – particularly meteorological radars – enable the long-term study of cloud and precipitation microphysics across large areas, providing insights into particle size, phase differentiation, hydrometeor classification, and vertical structure in MPCs. Combining multiple radar frequencies can further enhance these analyses, allowing techniques such as dual-wavelength ratios and differential attenuation to explore cloud microphysical properties in more detail. Here, we present the instrumental setup and preliminary findings from multi-frequency polarimetric radar observations collected during the CHOPIN campaign (CleanCloud Helmos OrograPhic sIte experimeNt). Measurements took place from October 2024 to January 2025 at Mount Helmos (Greece) in the framework of the Horizon Europe CleanCloud project. Three meteorological radars (X-, Ka-, and W-band) were deployed to capture radar moments and multi-wavelength polarimetric Doppler spectra, while in-situ instruments characterised aerosols, cloud condensation nuclei (CCNs) and ice nucleating particles (INPs) to study microphysical processes in mid-latitude MPCs over complex terrain, with a particular focus on SIP.

**ID: 120, Poster**

## Do crowdsourced data improve rainfall observations at the catchment scale? A Europe-wide assessment

1) Nathalie Rombeek* (Delft University of Technology), 2) Markus Hrachowitz (Delft University of Technology), 3) Davide Wüthrich (Delft University of Technology), 4) Remko Uijlenhoet (Delft University of Technology)

Accurate and timely precipitation data is key for early warning systems. Dedicated rain gauge networks from meteorological and hydrological services are often sparse and rainfall estimates from weather radars often contain substantial uncertainty and bias. Alternatively, rain gauges from personal weather stations (PWSs) (i.e. low-cost commercial devices), of which there are tens of thousands in Europe, can be utilized for this purpose. For this study we obtained a 1-year PWS dataset containing 5-min accumulations from the private company Netatmo, covering the period of 1 September 2019 to 31 August 2020. We investigate the performance of rain gauge data from PWSs covering more than 10,000 European river catchments, which are part of the EStreams dataset. Rainfall observations from PWSs are interpolated over the catchment areas. Results are compared to the real-time radar dataset covering Europe from the Operational Program on the Exchange of weather RAdar information (OPERA). The EURADCLIM (EUropean RADar CLIMatology), which is the European gauge-adjusted radar product, is used as a reference dataset. We investigate whether the added value of PWS data can be attributed to factors such as PWS network density, PWS distribution, land use, catchment size, topography, population density and climate regime.

**ID: 126, Poster**

## IcePolCKa - A Review

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Aim of the ICEPolCKa project was to exploit the synergy of two polarimetric research radars at two frequencies, the C-band POLDIRAD at DLR, Oberpfaffenhofen and the Ka-band Metek MIRA-35 at LMU Munich, as well as operational C-band radars from of Deutscher Wetterdienst DWD to study ice particle growth and precipitation formation. At a distance of 23 km between DLR and LMU the use of the two research radar systems allows targeted observations and coordinated scan patterns. Now, 6 years after the start of this project, we present a review.
We have developed a setup to systematically characterize differences between numerical weather models (WRF, 400 m grid spacing) and polarimetric radar observations for convective weather situations. This setup is used to evaluate 5 different microphysical methods of varying complexity (Thompson 2-mom, Thompson aerosol-aware, Morrison 2-mom, spectral bin (SBM), and P3). A cell-tracking algorithm applied to radar observed as well as modeled convective precipitation facilitates comparison on a cell object basis over a 30-day dataset. A statistical comparison of convective cell characteristics in observations and models was conducted. An analysis of high-impact weather events, including hail and heavy precipitation, was performed to assess the impact of differences in the cloud microphysics schemes on the prediction. Additionally, the automatic tracking of convective cells facilitated an analysis of the spatio-temporal development in simulations and observations.
The novel combination of polarimetric, multi-wavelength radar measurements has been used to retrieve ice microphysics information during stratiform precipitation events. The dual-wavelength ratio (DWR) obtained from C and Ka-band measurements provides information about the size of the detected ice particles. Comparing the radar measurements to T-Matrix scattering simulations for ice particles with varying aspect ratio (AR), median mass diameter (Dm) and ice water content (IWC) of their particle size distribution, a simple ice microphysics retrieval resolving the shape, the size and the mass of ice hydrometeors was developed.
Finally, we explored the possibility to combine vertically pointing Ka-band radar with DWD's national fully polarimetric Doppler C-band radar network. Beam-aware Columnar Vertical Profiles extracted from multiple C-band radars at different distances from the cloud radar and vertical profiles extracted from RHIs of dedicated C-band radars pointing to the cloud radar were compared and matched to the measurements of the cloud radar in order to demonstrate the added value of a vertical pointing cloud radar to the horizontally scanning national radar network.

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**ID: 92, Poster**

## Enhanced composition of X- and C-band radar data

1) Albert Oude Nijhuis* (SkyEcho B.V.), 2) Yann Dufournet (SkyEcho B.V.)

The improvement and quality assessment of radar-derived-rain products remains a tough challenge. In this presentation, the focus will be on the implementation of radar data quality parameters - specifically signal-to-noise-ratio (SNR), normalised coherent power (NCP) and the percentage of valid doppler bins - to label "bad quality radar cells". The goal of this is to ignore "bad quality radar cells", and enhance the final rainfall rate composite product. Bad quality radar cells can occur because of signal attenuation, radio interference, signal blockage, etc. The work is conducted on a rain composite that merges data coming from a set of Dutch radars (X and C-bands): the MESEWI X-band radar from TU Delft, the RIJNMOND X-band radar in Rotterdam, and the KNMI international realtime radar composite. PhiDp will be used for attenuation corrections, and KDP-algorithms will be applied for rainfall rate estimation. In the merging of X-band and C-band data, there is that one noticeable thing: there are places where the C-band composite data contains rain and the X-band composite does not. The most likely reason for this, is that the X-band radar data is acquired at lower altitudes, whereas the C-band composite is interpolated at some places from higher altitudes. To overcome this issue, a technique is applied where for a certain region low C-band values are removed. Finally, a comparison to raingauges is made for the assessment of the composite.

**ID: 142, Poster**

## Flux Observations for Process-Informed Quantitative Precipitation Estimates

1) Aimee Matland-Dixon* (The University of Oklahoma), 2) Pierre Kirstetter (The University of Oklahoma), 3) Robert Palmer (The University of Oklahoma)

Radar fast-scanning capabilities are uniquely positioned to capture the evolution of radar variables within an atmospheric vertical column due to short revisit times. This allows for the characterization of storm decorrelation times and the calculation of high-resolution temporal and spatial radar variable derivatives. Process rates are influenced by vertical mass flux, changes to condensed liquid water mass in time, and advection of the liquid water content. High temporal sampling can help to derive changes in liquid water content in time and space, allowing for estimates of precipitation rates at the surface and classification of processes in the atmosphere. This work presents a case study of observed precipitation in Norman, Oklahoma,and comments on the usefulness of phased array radar (PAR) for the estimation of process-informed precipitation rates.

**ID: 144, Poster**

## The Vertical Distribution of Particle Shape (VDPS) Method: Introduction, Application and Evaluation

1) Audrey Teisseire* (TROPOS), 2) Anne-Claire Billault-Roux (EPFL), 3) Teresa Vogl (Leipzig Institute for Meteorology (LIM), Leipzig University), 4) Kevin Ohneiser (TROPOS), 5) Patric Seifert (TROPOS), 6) Heike Kalesse-Los (Leipzig Institute for Meteorology (LIM), Leipzig University), 7) Anton Kötsche (Leipzig Institute for Meteorology (LIM), Leipzig University), 8) Maximilian Maahn (Leipzig Institute for Meteorology (LIM), Leipzig University), 9) Veronika Ettrichrätz (Leipzig Institute for Meteorology (LIM), Leipzig University), 10) Martin Radenz (TROPOS)

Observing the shape of ice particles is crucial for understanding cloud microphysical processes such as riming, aggregation, and depositional growth. The particle shape provides information about their formation history, growth mechanisms, and interactions with atmospheric conditions. In this study we present a new approach that utilizes polarimetric variables, from observations of a scanning polarimetric (Slanted Linear Depolarization Ratio (SLDR)-mode) cloud Doppler radar of type MIRA-35, to derive the vertical distribution of particle shape (VDPS) between top and base of mixed-phase cloud systems. This algorithm uses Range Height Indicator (RHI) scans from 30° to 90° elevation angle of SLDR which is sensible to the shape of particles. From the elevation dependency of SLDR the microphysical parameter polarizability ratio (i.e., density-weighted aspect ratio) is derived as a function of height. Based on the long-term observations, we found that the evolution of the shape between cloud top and base varies for different cloud and thermodynamic conditions. Generally, the shape gradient ranges from a pristine columnar or dendritic state at cloud top toward a more isometric shape at cloud base. Either aggregation or riming processes contribute to this vertical change of microphysical properties. Their quantitative characterization is challenging and, in this fact, requires knowledge about the fall velocity of the particles and the presence of supercooled liquid droplets, for which novel techniques are required in order to be detectable beyond lidar signal extinction.

In this study, we demonstrate the applicability of the VDPS method based on case studies acquired in Punta Arenas, Chile, and Eriswil, Switzerland, present its added value in the determination of aggregation and riming events in deep mixed-phase cloud systems, and provide an evaluation of the method comparing its results with in situ measurements. Given the increased availability of scanning SLDR cloud radar systems, we suggest to incorporate regular RHI scans into those systems in order to enable the application of the openly available VDPS method.

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## Session 1.B: From classical to integrated remote sensing. New retrieval and estimation techniques (e.g. fusion, Bayesian)

**ID: 106, Oral Presentation**

## A probabilistic AI-based merging of Commercial Microwave Link and Radar QPE

1) Julius Polz* (KIT/IMK-IFU&IMK-ASF), 2) Luca Glawion (KIT/IMK-IFU), 3) Maximilian Graf (Deutscher Wetterdienst), 4) Mst Mahfuja Akter (Institute for Geosciences, Department of Meteorology, University of Bonn), 5) Nico Blettner (KIT/IMK-IFU), 6) Silke Trömel (Institute for Geosciences, Department of Meteorology, University of Bonn), 7) Harald Kunstmann (KIT and University of Augsburg), 8) Christian Chwala (KIT (IMK-IFU))

Commercial Microwave Links (CMLs) provide path-integrated attenuation estimates close to the ground which are closely related to the path-averaged rainfall intensity. Therefore, the combination of CMLs with area-wide weather radar observations, each with its strengths and weaknesses, enables us to further improve the accuracy of rainfall maps. Weather radars measure at increasing heights with increasing distance from the radar. Thus, quantitative precipitation estimation (QPE) may show biases due to for example advection, strong up- and downdrafts, size sorting or melting processes. At the same time, CMLs require extensive quality control to deliver robust QPE. QPE from both sources have benefitted from the application of AI based methods in the past.
In this study, we extend ResRadNet, a deep learning framework to predict rain gauge estimates on the ground based on radar-derived QPE and the measurement height, by using CML-based QPE as additional model input. Training the model using rain gauges as an accurate point-scale measurement, it is enabled to subsequently provide improved surface estimates without further gauge-adjustments. Additionally, we develop a new Continuous Ranked Probability Score (CRPS) based objective function to enable skillful ensemble predictions and estimate the uncertainty of the ground-adjustment. Using the RADOLAN-RY precipitation product, derived from the C-band radar network of the German Weather Service (DWD), and a large CML network with 3900 link paths, our results demonstrate that the use of CMLs significantly reduces the biases of ResRadNet QPE. We further present the impact of the new objective function on the prediction of extremes and how to calibrate the ensemble variance. Combined rainfall maps are presented and discussed for recent flooding events in Germany.

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**ID: 113, Oral Presentation**

## Hydrometeor classification based on cloud radar Doppler spectrum peaks using the PEAKO-peakTree toolkit

1) Teresa Vogl* (Leipzig Institute for Meteorology (LIM), Leipzig University), 2) Martin Radenz (TROPOS), 3) Moritz Lochmann (Leipzig Institute for Meteorology (LIM), Leipzig University), 4) Heike Kalesse-Los (Leipzig Institute for Meteorology (LIM), Leipzig University)

Microphysical processes in clouds like ice formation, riming, and ice multiplication can be investigated through cloud radar Doppler spectra: When hydrometeor types within a cloud radar observation volume have sufficiently different terminal fall velocities, they generate individual Doppler spectrum peaks. By separating these peaks, valuable information on the fall velocity, size, number, and potentially the shape of hydrometeors can be extracted. This separation depends both on radar settings and atmospheric dynamics (Vogl and Radenz et al., 2024). Here, we are using two algorithms, PEAKO and peakTree, for analyzing Doppler spectrum peaks. PEAKO is a supervised machine learning tool, trained to optimize peak detection for specific radar settings, while peakTree organizes and interprets these peaks using parameters learned from PEAKO. Based on the moments of each extracted sub-peak, hydrometeor types can be assigned to peaks that have properties typical of liquid cloud droplets, columnar ice and rimed ice. This novel cloud radar Doppler spectrum peak-based hydrometeor classification mask can be used for detailed case studies, e.g. for tracking hydrometeor populations through the cloud along Doppler spectrum peak-based fall-streaks. Furthermore, statistics on the occurrence of different hydrometeor types at different sites and temperature ranges can be derived.

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**ID: 22, Oral Presentation**

## Investigating the Origin of W-Band Radar KDP Signatures Inside and Below the Dendritic Growth Layer

1) Anton Kötsche (Leipzig Institute for Meteorology (LIM), Leipzig University), 2) Alexander Myagkov (RPG Radiometer Physics GmbH), 3) Maximilian Maahn* (Leipzig Institute for Meteorology (LIM), Leipzig University), 4) Veronika Ettrichrätz (Leipzig Institute for Meteorology (LIM), Leipzig University), 5) Teresa Vogl (Leipzig Institute for Meteorology (LIM), Leipzig University), 6) Alexander Ryzhkov (NSSL, Norman), 7) Petar Bukovcic (NSSL, Norman, OK, USA), 8) Leonie von Terzi (Meteorological Institute, Ludwig-Maximilians-Universität in Munich), 9) Davide Ori (Institute of Geophysics and Meteorology, University of Cologne), 10) Heike Kalesse-Los (Leipzig Institute for Meteorology (LIM), Leipzig University)

In snow, the specific differential phase (KDP) measured by dual-polarimetric cloud radars is often considered an indicator of high concentrations of small, nonspherical particles. However, KDP also depends on other hydrometeor characteristics such as density, orientation, phase, and size. Determining the contributions of various hydrometeors to observed KDP values is challenging and typically addressed through modeling approaches. During the winter of 2022-2023, we deployed an innovative simultaneous-transmission-simultaneous-reception (STSR) Doppler W-band cloud radar (LIMRAD94) operated at 40deg elevation angle alongside a novel video in situ snowfall sensor (VISSS) in the Colorado Rocky Mountains. These observations supplemented the extensive measurements of the Atmospheric Radiation Measurement (ARM) Surface Atmosphere Integrated Field Laboratory (SAIL) campaign, which also featured Ka-band and X-band radars. The VISSS provided valuable particle data, including size, number, shape, and complexity. Our analysis of high-KDP fall streaks, combined with in situ data from the VISSS, revealed that similar KDP magnitudes were produced by particle populations with significantly different number concentrations and mean mass-weighted particle diameters. By analyzing additional radar variables such as spectral differential reflectivity, reflectivity, spectral width, and correlation coefficient, we aim to understand when and how small and large particles contribute to the observed KDP magnitude. Moreover, we explore the influence of external factors, such as turbulence layers and synoptic fronts on polarimetric radar measurements.

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**ID: 27, Oral Presentation**

## Processing of Doppler spectra collected by an airborne cloud radar

1) Ulrike Romatschke* (NSF National Center for Atmospheric Research), 2) Paul Romatschke (University of Colorado, Boulder), 3) Matthew Hayman (NSF National Center for Atmospheric Research), 4) Michael Dixon (NSF National Center for Atmospheric Research)

Radar Doppler spectra from vertically-pointing cloud radars have been successfully used to derive physical and microphysical properties of clouds and precipitation, such as air motion, particle fall speed, or cloud-drop and drizzle parameters. The majority of past studies utilized spectral observations of stratiform clouds from ground-based radar systems. Doppler spectra from airborne radars are rarely used because they pose special challenges: Because of the finite beam width of radars, the horizontal wind component, which is dominated by the high speed of an aircraft, causes a broadening of the airborne spectra, even when the radar is pointing exactly vertically. Using observations from the airborne HIAPER Cloud Radar (HCR), we developed a robust technique to correct Doppler spectra for broadening caused by aircraft motion. From the corrected spectra, we calculate high-quality higher-order moments, such as skewness and kurtosis, and other spectral parameters. The development of this processing method is the first step towards our goal of providing higher-order moments, and other spectral parameters, for all HCR observations on a routine basis. HCR has been deployed in five major field campaigns, reaching from the Southern Ocean to the Central American tropics, sampling a vast variety of cloud types. By making spectral radar products derived from clouds sampled in different climatic regions easily accessible, we aim to increase their use by the scientific community. Better utilization of spectral products in cloud research will improve our understanding of their microphysical and kinematic implications, and enhance their use in retrieval algorithms.

**ID: 108, Oral Presentation**

## Quantifying Riming by Combining the Video In Situ Snowfall Sensor with Cloud Radar Observations

1) Maximilian Maahn* (Leipzig Institute for Meteorology (LIM), Leipzig University), 2) Nina Maherndl (Leipzig Institute for Meteorology (LIM), Leipzig University), 3) Nils Pfeifer (Leipzig Institute for Meteorology (LIM), Leipzig University), 4) Sabine Hörnig (Leipzig Institute for Meteorology (LIM), Leipzig University)

We do not know the exact pathways through which ice, liquid, cloud dynamics, and aerosols are interacting in clouds while forming snowfall. Riming, the freezing of droplets onto ice crystals, is likely one of the most important snowfall formation mechanisms. This is not only because riming is an efficient particle mass growth mechanism, but also because riming is related to secondary ice processes that increase the number of ice particles. Further, riming changes the density of ice particles impacting the particle scattering properties so that implicit or explicit assumptions about riming are required when using passive or active microwave observations of snowfall. Quantifying the riming process is challenging because it requires separating riming from other particle growth mechanisms and snowfall is generally difficult to observe. Various methods based on in situ and cloud radar observations have been proposed, but uncertainties are generally high. Here, we present a method to estimate riming by combining Video In Situ Snowfall Sensor (VISSS) and W-band cloud radar observations. The VISSS was developed to determine particle shape, size, and velocity distributions. Different from other sensors, the VISSS minimizes uncertainties by using two-dimensional high-resolution images, a large measurement volume, and a design limiting the impact of wind. We will apply the retrieval to various datasets to explore the relation between riming and liquid water path and turbulence.

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**ID: 24, Oral Presentation**

### Impact of seeder-feeder cloud interaction on precipitation formation over the Swiss plateau: a case study and statistics based on extensive remote-sensing, in situ and model data

1) Kevin Ohneiser* (TROPOS), 2) Dietrich Althausen (TROPOS), 3) Albert Ansmann (TROPOS), 4) Holger Baars (TROPOS), 5) Ronny Engelmann (TROPOS), 6) Veronika Ettrichrätz (Leipzig Institute for Meteorology (LIM), Leipzig University), 7) Christopher Fuchs (ETHZ), 8) Tom Gaudek (TROPOS), 9) Hannes Griesche (TROPOS), 10) Majid Hajipour (TROPOS), 11) Jan Henneberger (ETHZ), 12) Julian Hofer (TROPOS), 13) Heike Kalesse-Los (Leipzig Institute for Meteorology (LIM), Leipzig University), 14) Anton Kötsche (Leipzig Institute for Meteorology (LIM), Leipzig University), 15) Ulrike Lohmann (ETHZ), 16) Max Maahn (Leipzig Institute for Meteorology (LIM), Leipzig University), 17) Nina Maherndl (Leipzig Institute for Meteorology (LIM), Leipzig University), 18) Anna Miller (ETHZ), 19) Nadja Omanovic (ETHZ), 20) Martin Radenz (TROPOS), 21) Fabiola Ramelli (ETHZ), 22) Willi Schimmel (TROPOS), 23) Patric Seifert (TROPOS), 24) Fabian Senf (TROPOS), 25) Annett Skupin (TROPOS), 26) Robert Spirig (ETHZ), 27) Teresa Vogl (Leipzig Institute for Meteorology (LIM), Leipzig University), 28) Huiying Zhang (ETHZ)

The PolarCAP (Polarimetric Radar Signatures of Ice Formation Pathways from Controlled Aerosol Perturbations) project makes use of a large set of remote-sensing and in-situ measurement devices in an ideal natural laboratory in the center of Switzerland. Targeted scenarios are so-called Bise weather situations, when northeasterly winds advect moist near-surface air masses over the Swiss Plateau such that there is a frequent chance to observe slightly supercooled low-level stratus clouds in an environment with very low INP concentrations. PolarCAP is implemented in close collaboration with the external ERC research project CLOUDLAB of ETH Zurich. CLOUDLAB makes use of these ideal natural requirements and conducts controlled seeding experiments.

Within the PolarCAP project, the remote sensing equipment of LACROS (Leipzig Aerosol and Cloud Remote Observations System) was installed in Eriswil, Switzerland during two winter campaigns between 2022 and 2024. Techniques for Doppler peak separation, and multi-wavelength analysis, and retrievals of ice-crystal size distributions and particle habits, all based on scanning polarimetric cloud radar observations, were combined with fall-streak tracking and liquid-water retrievals to obtain a comprehensive picture of the cloud evolution. Evaluation data was obtained with ground-based in-situ VISSS (Video In Situ Snowfall Sensor) and 2DVD (two-dimensional video disdrometer). These were used to challenge the remote-sensing-based retrievals.

This presentation focuses on a seeder-feeder case study on 8 Jan 2024, when a moist warm-frontal cloud system, which was advected from southerly direction, interacted with the prevailing low-level Bise cloud deck. The PolarCAP/CLOUDLAB setup was ideal to apply several advanced remote-sensing techniques and retrieval algorithms, including fall streak tracking, Doppler peak separation, and dual-wavelength applications. Results indicated that a large portion of the ice mass was rimed, attributed to the persistent coexistence of falling ice seeds within low-level supercooled liquid water layers. Only the interaction of the seeder and feeder clouds resulted in a significant precipitation enhancement. A comparison with ICON NWP simulations revealed that seeding efficiency was underestimated in the model, whereas the model setup overestimated precipitation production in the Bise cloud. In addition to the detailed case study, we present a statistics and relevance of all seeder-feeder scenarios which were observed during

the PolarCAP/CLOUDLAB winter experiments in 2022/2023 and 2023/2024.

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**ID: 45, Oral Presentation**

## The role of rain evaporation for the energy and radiation budget of the trades

1) Nina Robbins-Blanch* (University of Hamburg), 2) Florian Poydenot (University of Hamburg), 3) Claudia Acquistapace (University of Cologne), 4) Sabrina Schnitt (University of Cologne), 5) Raphaela Vogel (University of Hamburg)

This study investigates the role of rain evaporation in shaping cloud cover and influencing the energy and radiation budget in the trade cumulus region. Although research has advanced our understanding of shallow trade cumulus clouds, the influence of mesoscale cloud organization on cloud feedbacks and the hydrological cycle remains uncertain. Rain re-evaporation can drive mesoscale structures, generating downdrafts and cold pools that form cloud-free areas encircled by cloud arcs. Yet, the relationships between cold pool characteristics, initial rain evaporation, and their effects on cloud cover and the radiative budget are not well understood, largely due to limitations in observational data and model fidelity.
To address this gap, we will develop a long-term dataset of rain evaporation rates using measurements from the Barbados Cloud Observatory. By examining vertical differences in drop size distributions, we aim to characterize the vertical structure of rain evaporation and cooling rates. This work leverages a dual-frequency method with Ka-W band Doppler spectra, chosen for its capacity to address challenges related to attenuation, calibration, and turbulence. We will consider this dual-frequency retrieval as a "ground truth," using it to evaluate the reliability of other retrieval methods, including a single-frequency approach combined with a vertical velocity retrieval and an observationally-constrained one-dimensional rain shaft model. Observations from the ORCESTRA (Organized Convection and EarthCare Studies over the Tropical Atlantic) campaign and its SCORE (Sub-Cloud Observations of Rain Evaporation) sub-campaign will serve as intensive testing phases.
Ultimately, this dataset will enable quantification of the magnitude and vertical structure of rain evaporation, explore their dependence on ambient humidity and rain intensity, and assess the impact of evaporation profiles on boundary layer stability, cold pool dynamics, and cloudiness.

**ID: 21, Oral Presentation**

## Exploring Total Column Water Vapor retrievals from Satellite-Based Near-Infrared Measurements in Pre-Convective Environments

1) Cintia Carbajal Henken* (Freie Universität Berlin), 2) Jan El Kassar (Freie Universität Berlin), 3) Rene Preusker (Freie Universität Berlin)

Satellite-based near-infrared (NIR) measurements within the water vapor absorption band at around 0.9 microns and adjacent window bands are used to retrieve total column water vapor (TCWV) in clear-sky, daytime conditions. The sensitivity of the ratio of these measurements increases towards the surface, allowing detailed observation of atmospheric moisture variability down to the boundary layer. Low-level moisture plays a crucial role in the formation of deep convection and accompanying severe weather like heavy precipitation. Monitoring local to regional changes in (boundary layer) moisture, e.g. increase of moisture in convergence zones, can serve as an early indicator of convective development before the onset of clouds and precipitation. The predictive potential of these TCWV fields has been demonstrated for a set of cases using spatially high-resolution TCWV retrievals obtained from morning-time measurements from the Ocean and Land Colour Instrument (OLCI) aboard the polar-orbiting Sentinel-3 satellites. OLCI's TCWV fields at 300m resolution capture small-scale convective features within the boundary layer. The OLCI TCWV retrieval retrieval framework is being adapted for the Flexible Combined Imager (FCI) on the new Meteosat Third Generation (MTG) satellite. FCI is the first geostationary instrument to include this NIR water vapor absorption band, offering an unprecedented opportunity to generate high temporal and spatial resolution TCWV datasets with large spatial coverage, enabling a more comprehensive monitoring and characterization of local to regional TCWV spatial variabilities and temporal changes, particularly in pre-convective environments. Through the assessment of these TCWV fields, their evolution and how they relate to convective development later on, we hope to offer valuable information for nowcasting methods.

### Acknowledgements

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**ID: 61, Oral Presentation**

## Wind drift effect on radar data through analysis of individual drop trajectories using 3D+1 innovative wind product

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Hydro-meteorologists and practitioners in charge of storm water management in complex areas such as cities or mountains are interested in high resolution space-time precipitation rainfall data, typically few hundreds of meters in space and few minutes in time. A crucial issue to get accurate data is the wind drift effect. Indeed, weather radars measure rainfall in altitude, and drops are advected by wind during their fall which affects the location of the measured field. This drift can be of few kilometres.
A recent study explored this issue through the simulation of individual drops trajectories in 3D space and time relying on: (i) an explicit numerical scheme to solve the non linear governing equations of rain drop's motion which relates the acceleration to the forces of gravity and buoyancy along with the drag force; (ii) a simplistic wind simulation approach relying on 100 Hz 3D sonic anemometer and scaling laws. Universal multifractals are used to quantify retrieved results. This physically based and mathematically robust framework has been extensively used to analyse and simulate geophysical fields extremely variable over wide range of space-time scales as wind and rainfall. Implementation of this model for drop trajectories enabled to show that multifractal features of input wind are retrieved also on drop velocities with an additional fractional integration. Large drops exhibit greater level of fractional integration. Simulating the fall of drops from an altitude of 1500 m, it was possible to show that for a strong wind event, drops located within a radar gate in altitude during 5 min are spread on the ground over an area of the size of a few kilometres which corresponds to numerous radar pixels. Furthermore drops of various sizes do not reach ground at same location.
In this study, the same numerical scheme is implemented using as space-time wind input a novel 3D product of Central Weather Agency, Taiwan. It provides vector wind over voxels of size approximately 1 km in horizontal direction, 500 meter in the vertical every 10 min. In a first step, trajectories of individual drops of various size and various initial locations are simulated. Multifractal features of simulated velocities are quantified and compared against expectations. Their spread over ground level is quantified as well as its evolution during the rainfall event. In a second step, these results are used to explore and interpret rainfall patterns observed on the 3D+1 available radar data. At last, consequences of these finds on the wind drift effect on radar rainfall data are discussed.

### Acknowledgements

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**ID: 90, Oral Presentation**

## Melting Layer and Riming Detection from Vertically Pointing C-band Radar Observations

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The German weather radar network consists of 17 dual-polarization Doppler C-band radars that are operated by the German Weather Service (DWD). These radars are evenly distributed across Germany and record data continuously. One component of the scanning cycle is a vertically looking 'birdbath' scan, which is performed every 5 minutes for a duration of 15 seconds. While the zenith configuration is common for Ka- and W-band cloud research radars, it has mostly been used to calibrate ZDR in operational weather radars so far. Despite the lower temporal resolution, comparisons between zenith observations from cloud radars and weather-radar birdbath scans in close proximity with each other reveal remarkable agreement in the recorded large-scale patterns for various weather systems. In this contribution, we present two data products that can be derived from these scans: A melting layer detection and a classification of rimed particles. Both products make use of the Doppler velocity of falling hydrometeors. The melting layer detection is based on the sharp increase in Doppler velocity in the melting region, while the riming detection algorithm is searching for continuous regions of unusually high (>1.5 m/s) Doppler velocity above the melting layer. Unlike many cloud research facilities, there is generally no additional meteorological instrumentation at the operational sites, so our products must work solely on radar data. Both algorithms are designed to work without manual support, so that they can be used operationally. We will compare the melting layer and riming products to similar implementations previously developed for cloud radars and discuss the challenges and modifications needed to apply the algorithms to the operational weather radars. One benefit of transferring research products to operational radars is the large spatial coverage of such national weather radar networks (about 150 weather radar sites with profiling capabilities across Europe).

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**ID: 71, Oral Presentation**

## Hydrometeor partitioning ratios for polarimetric ground-based and dual-frequency space-borne and radar observations

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Broadly used radar-based Hydrometeor Classification (HMC) algorithms solely identify the dominant hydrometeor class within a resolved radar volume. More recently, however, methods have been developed to estimate the proportions of individual hydrometeor types (hydrometeor partitioning ratios, HPR) within the mixture. These advanced algorithms (HMC-DP) are exploiting dual-polarization (DP) measurements of ground-based weather radars (GR), while similar algorithms for space-borne radar (SR) observations with dual-frequency (DF) capabilities are not yet available. In this study, we exploit the combination of DF SR and DP GR to develop an algorithm for HPR estimation based on satellite DF observations (HMC-DF) and to improve the HMC-DP based on GR DP observation. The evaluation of HPR retrievals, derived from either GR or SR, is challenging. However, this study also presents an evaluation of the HPR retrievals derived from HMC-DP and HMC-DF. Therefore, the DP observations of NEXRADs WSR-88D GRs are matched with the measurements of the Dual-frequency Precipitation Radar (DPR) of the Global Precipitation Measurement (GPM) core satellite. The matched volumes, represented by averaged DF or DP measured variables, contain a few SR but several hundred GR measurement volumes, depending on the distance to the GR. This large difference in observation resolution allows the determination of quasi HPR (qHPR) per matched volume obtained from the dominant hydrometeor types (standard HMC) classified by the GR. The matched DF and DP are utilized to derive centroids and covariance matrices for each individual hydrometeor class based on the qHPR. These centroids and covariance matrices serve as the basis for the HMC-DP and HMC-DF algorithms and their HPR retrievals, which in turn are verified with the qHPR. Results demonstrate a high degree of agreement between the HPR distributions derived with HMC-DF and HMC-DP. The HPR derived with HMC-DP show a higher correlation with the qHPR in comparison to the HPR derived with HMC-DF. This is due to the fact that DP, compared to the DF observations, provide additional information, for example, regarding the orientation, shape and homogeneity of the hydrometeors within the measurement volume. However, both HMC-DF and HMC-DP underestimate snow with biases of -5%, overestimate HPRs of graupel with biases up to 3% and show low correlations of 0.37 for DP and 0.16 for DF estimates of big drops HPR.

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**ID: 114, Oral Presentation**

## Developement of a microphyscial retrieval based on beam-aware columnar vertical profiles: Combining side-looking polarimetry with vertical radar measurements

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The understanding of microphysical processes and properties in clouds plays a substantial role in the improvement of existing numerical weather models and forecasting. To gain access to these quantities deep within clouds, microphysical retrievals based on radar measurements are indispensable tools. Single-wavelength radar measurements, however, are not enough to properly constrain the microphysical properties of hydrometeors like size and shape alone and therefore need to be paired with additional observations like multi-wavelength or polarimetric quantities. While polarimetric quantities are mainly useful from an oblique perspective, multi-wavelength or doppler fall-speed observations are best made vertically and from close distance.

To tackle this observational dilemma we employ the previously developed method of beam-aware columnar vertical profiles (BA-CVPs) to combine a vertically pointing cloud radar in the Ka-band with operational measurements of two side-looking polarization Doppler weather radars in the C-band which are part of the national German radar network operated by the Deutscher Wetterdienst. In the next step a microphysical retrieval is developed incorporating existing approaches based on dual-wavelength ratio and differential reflectivity measurements to study the size and shape of hydrometeors. The measurement geometry grants the opportunity to explore the inclusion of linear depolarisation ratio and Doppler fallspeed velocity measurements in the retrieval to further constrain existing ambiguities. Retrieval results based on simple T-matrix scattering simulations are compared to results using more sophisticated discrete dipole approximation simulations weighing computational cost against accurate scattering properties of simulated hydrometeors.

The findings of this study in form of more accurate information about ice hydrometeors based on multi-frequency radar measurements can ultimately be used to improve existing numerical weather models with regards to ice growth processes and their representation within the models. Naturally, the retrieval can be applied to any other measurement geometry that combines side- and vertically-pointing radar measurements, e.g. BA-CVPs of operational weather radars along the flightpaths of airborne or satellite radar measurements.

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**ID: 28, Oral Presentation**

## What can radars tell us about snowfall microphysics? Insights from a MCMC framework

1) Anne-Claire Billault-Roux (Environmental remote sensing laboratory, EPFL, MeteoSwiss), 2) Alexis Berne* (Environmental remote sensing laboratory, EPFL)

Multi-frequency and Doppler spectral radars are valuable tools to retrieve information on the microphysics of precipitation, and snowfall in particular. However, estimating ice phase microphysics from radar measurements is an ill-posed problem, meaning that different sets of microphysical properties may correspond to the same radar observations. For most retrieval approaches, the uncertainty related to this ill-posedness is difficult to quantify; furthermore, they typically rely on assumptions regarding microphysics or scattering properties, whose impact on the retrieval is usually unknown. In this work, we use simulated radar measurements and the Markov chain Monte Carlo (MCMC) framework to retrieve microphysical information from triple-frequency radar Doppler spectra, with minimal assumptions on the mathematical and physical properties of the system. While this approach is not designed for operational implementation because of its computational cost, it allows to gain insights into the sources of uncertainty and ill-posedness of this radar retrieval problem. We analyze the posterior distributions retrieved from 10 representative examples of simulated measurements. Our results show that certain microphysical variables like the effective diameter may be relatively well constrained, while others are far more uncertain, such as the shape parameter when a gamma particle size distribution (PSD) is assumed. The analysis also reveals relevant correlations in the multivariate posterior distribution, showing how microphysical descriptors are entangled in the retrieval. We then use this Bayesian framework to analyze the sensitivity of the retrieval to assumptions regarding atmospheric effects, radar vertical alignment, microphysical properties such as the mass-size relation or PSD shape, or scattering approximations. We also investigate the special case of bimodal Doppler spectra, where information regarding two hydrometeor populations is merged, and discuss to which extent this information may be recovered. With this work, we improve our understanding regarding the information content of radar Doppler spectra and the intrinsic limitations of microphysical retrievals.

**ID: 77, Poster**

## Addressing QPE Limitations with Solid State Transmitter X-Band Radar

1) Nicolás Andrés Chaves González* (Politecnico di Milano), 2) Alessandro Ceppi (Politecnico di Milano), 3) Carlo De Michele (Politecnico di Milano), 4) Giovanni Ravazzani (Politecnico di Milano), 5) Antioco Vargiu (ARPA Lombardia)

Radar measurements for precipitation estimation are essential for capturing the spatial variability of rainfall, which in turn strengthens precipitation forecasts and hydrological applications. This study focuses on quantitative precipitation estimation (QPE) using radar-based measurements in the Lombardy Region (north of Italy), assessing their limitations and defining optimal configurations. Specifically, data from two newly installed X-band radars with solid-state transmitters operated by the Regional Environmental Protection Agency (ARPA Lombardia) were analyzed.
The study aims to determine radar settings that yield optimal QPE at an operational level and explore post-processing solutions to mitigate radar limitations, particularly during extreme precipitation events that may cause flooding. The methodology is twofold: first, to establish radar configurations that relate rainfall intensity with radar data effectively, and second, to identify and address radar limitations during severe events, focusing on attenuation correction, signal extinction, and integration with third-party data sources.
An extreme precipitation event affecting Milan's hydraulic node was analyzed, highlighting areas for radar network improvement via post-processing techniques that could facilitate future hydrological modeling. Comparisons among QPE estimates include basic Z-R and polarimetric relationships, alongside Z-R matching methods from previous studies.
The study provides a foundation for operational QPE optimization and suggests strategies for overcoming radar limitations in extreme precipitation events. This framework also supports further advancements, such as integrating the real-time rain gauge network to enhance flood forecasting accuracy.

**ID: 40, Poster**

## Data-driven classification of polarised weather radar observations

1) Maryna Lukach* (Royal Meteorological Institute of Belgium (RMI), National Centre for Atmospheric Science (NCAS), University of Leeds), 2) Lindsay Bennett (National Centre for Atmospheric Science (NCAS), University of Leeds), 3) David Dufton (National Centre for Atmospheric Science (NCAS), University of Leeds), 4) Mansi Mungee (University of Leeds), 5) Ryan Neely III (National Centre for Atmospheric Science (NCAS), University of Leeds)

This contribution presents machine learning advancements in application of hierarchical clustering to the Met Office's extensive archive of weather radar data. Building on the successful classification of weather radar observations using novel data-driven technique, we delve into the potential of these methods in analyzing C-Band radars' big-scale datasets. This approach has demonstrated robust and accurate performance, promising significant improvements in the UK's quantitative observation capabilities. The poster highlights recent advancements in using weather radar data, particularly from the NCAS X-band and the C-band of the Met Office radar network, for a more nuanced understanding of spatial and temporal patterns in various atmospherical phenomena. Our findings underscoring the importance of integrating advanced clustering techniques in environmental science.

**ID: 57, Poster**

## The GPM-GEO Archive: A Multimodal Remote Sensing Dataset for Cloud and Precipitation Research

1) Gionata Ghiggi* (EPFL), 2) Alexis Berne (Environmental remote sensing laboratory, EPFL)

The GPM-GEO archive is a unique analysis-ready dataset that co-locates third-generation geostationary (GEO) satellite multispectral visible/infrared (VIS/IR) imagery and cloud products, with precipitation spaceborne measurements acquired by the Global Precipitation Measurement Mission (GPM) Dual-frequency Precipitation Radar (DPR). The dataset has been created to encourage synergistic and collaborative use of multiple remote sensing data sources, to enable a broad range of studies in cloud and precipitation research, and to improve how we monitor and measure precipitation from space.
At the global scale, the spaceborne radar provides the best available instantaneous precipitation measurements, while geostationary imagers provide multispectral information of cloud-top spatial patterns evolution at high spatial (1 km) and temporal (10 minutes) resolutions. GPM-GEO provides the largest global reference database for the training and calibration of spatio-temporal data-driven models which can compensate for the lack of physical understanding and theoretical relationship between the GEO-sensed VIS/IR radiances and the precipitation geophysical quantities of interest. The GPM-GEO archive will therefore support the development of new artificial intelligence algorithms for the GEO monitoring and quantification of precipitation as well as the near-real-time detection of severe weather phenomena such as convective and hail storms. This will promote the design of new early warning systems and will help reduce the exposure of vulnerable communities to the impact of extreme weather events.
The GPM-GEO dataset, available from April 2019 to present, is currently produced using the GOES and HIMAWARI satellites data. Calibrated radiances for the 16 bands of the Advanced Baseline Imager and the Advanced Himawari Imager sensors as well as GEO clouds, precipitation and lightning products are collocated and remapped onto the GPM DPR swath. For each GPM overpass within the GEO field of view, the GPM-GEO dataset includes the GEO imagery acquired every 10 minutes between -40 to +20 minutes from the GPM DPR scanning time.
To facilitate the exploration of the archive, a python software provides tools for dataset manipulation, image extraction as well as interactive visualization. A graphical user interface allows the creation of meteorological composites, the overlay of custom precipitation and cloud products, and the simultaneous exploration of the spatial, temporal and spectral dimensions of the data. Finally, the modular structure of the software designed for the production of the GPM-GEO archive is easily adaptable to be reused for the collocation other satellite sensors.

**ID: 100, Poster**

## Non-parametric Estimation of Drop-Size Distribution Profiles Using Cloud Radar Spectral Polarimetry

1) Tatiana Nomokonova* (RPG Radiometer Physics GmbH), 2) Michael Frech (Meteorological Observatory Hohenpeißenberg, Deutscher Wetterdienst), 3) Alexander Myagkov (RPG Radiometer Physics GmbH)

Polarimetric cloud radar has emerged as a crucial instrument for advanced cloud and precipitation monitoring. These radars provide a comprehensive set of radar observables similar to those of traditional polarimetric meteorological radars, with the added benefit of spectral resolution. This means that measurements are taken independently for particles within the same resolution volume but moving at different velocities relative to the radar. Since particle velocity correlates with size, spectral polarimetric observations form the basis for sophisticated retrieval techniques. The high signal-to-noise ratio and fine Doppler resolution (on the order of a few cm/s) enhance the information content of cloud radar data. This study introduces a non-parametric method for profiling drop-size distributions. The variational approach used builds on existing techniques developed for dual-frequency spectral observations and spectral polarimetric observations from centimeter-wavelength radars. The retrieval method is applied to data from a collaborative measurement campaign by the German Weather Service (DWD) and Radiometer Physics GmbH. Conducted at the DWD meteorological observatory in Hohenpeißenberg, Germany in 2021, the campaign's dataset enables evaluation of the retrieval results using a range of in situ and remote-sensing instruments.

**ID: 116, Poster**

## Maximum-Likelihood and Hamiltonian Monte Carlo Techniques to Doppler Moment Estimation for Precipitation using Weather Radar Echoes

1) Tworit Dash* (Delft University of Technology), 2) Hans Driessen (Delft University of Technology), 3) Oleg Krasnov (Delft University of Technology), 4) Alexander Yarovoy (Delft University of Technology)

Doppler moment estimation for precipitation with classical weather radars is a known problem, and estimation techniques exist to address it. However, such non-parametric retrieval techniques require long observation intervals. Therefore, the methods need further development with changing configurations for modern weather radars with fast azimuthal scans and phased array architecture. In this work, we focus on accurately estimating the Doppler moments only with a limited time on target as realized in fast azimuthally scanning radars. A maximum likelihood and a Bayesian inference approach are proposed in this work, where the power spectral densities (PSD) for the time series of the radar echoes act as measurements. A semi-analytical model of the expected value of the PSD is proposed. This approach is called the "Parametric Spectrum Estimator (PSE)". A log-likelihood cost is then formulated using the principles of spectrum estimation for random processes. Then, an inverse problem is formulated where this likelihood is maximized for the parameter retrieval. These PSD measurements can be incoherent, e.g., from several azimuthal scans. Let us denote the PSDs as $\mathbf{Z}^{(\mathrm{PSD})}$ having a dimension of $(L \times N)$, where $L$ is the number of azimuthal scans, and $N$ is the number of echoes in time for a specific resolution volume. Then, the inverse problem is defined as:

$$\hat{\theta} = \arg\max_{\theta} \log(p(\mathbf{Z}^{(\mathrm{PSD})} \,|\, \theta)),$$

where $\theta$ contains all the parameters; in this case, they are the Doppler moments (reflectivity, mean Doppler velocity and Doppler spectrum width).
Two different techniques are employed for the inverse problem:

1. Maximum Likelihood Estimation (MLE)
2. Markov Chain Monte Carlo (MCMC) with Hamiltonian Monte Carlo technique (HMC)

The difference between the two approaches is that the HMC also provides an estimate of the posterior distribution of the estimated parameters as it is a Bayesian inference approach. It is shown that the proposed methods improve the estimates substantially by reducing the bias. In addition, unlike the non-parametric approaches, the proposed approach can accommodate incoherent PSD measurements from several fast azimuthal scans.

# Session 2.A: Enhancing process understanding. New observations for modeling and parameterization development

**ID: 91, Oral Presentation**

## A statistical evaluation of cloud microphysics schemes in a numerical weather prediction model with polarimetric radar observations

1) Gregor Köcher* (Meteorological Institute, Ludwig-Maximilians-Universität München), 2) Tobias Zinner (Meteorological Institute, Ludwig-Maximilians-Universität München), 3) Florian Ewald (Deutsches Zentrum für Luft- und Raumfahrt (DLR), Oberpfaffenhofen), 4) Christian Heske (Deutsches Zentrum für Luft- und Raumfahrt (DLR), Oberpfaffenhofen)

Accurate representation of microphysical processes in clouds is crucial for reducing uncertainty in precipitation forecasts. Towards improving the prediction of convective precipitation, we developed a systematic framework for statistically evaluating cloud microphysical parameterizations in a numerical weather model using polarimetric radar observations from the German C-band radar network. Polarimetric radar observations are sensitive to cloud particle properties, such as particle shape, phase, or density, and are thus well suited for evaluating cloud microphysics. This study specifically targets high-impact weather events, such as hail and convective rain. Convective weather is particularly difficult to predict and the choice of the microphysical parameterizations significantly impacts the prediction of important characteristics of convective systems. At the same time, high-impact weather events have the potential to cause massive damage to both people and property.
The observational data for this study were collected using two polarimetric research radar systems in the Munich area of southern Germany, operating at C- and Ka-band frequencies, and a complementary polarimetric C-band radar operated by the German Meteorological Service (DWD). To evaluate the performance of cloud microphysics parameterizations in predicting high-impact weather events, a convection-permitting regional weather model setup has been developed, employing five microphysics schemes of varying complexity (double-moment, spectral bin, particle property prediction (P3)). The simulation of polarimetric radar signals consistent with the simulated cloud properties was achieved by applying a polarimetric radar forward operator. Convective cell objects are identified and tracked in both the model and radar data sets using an automated cell tracking algorithm. This facilitates Lagrangian tracking of individual convective cells, which permits the statistical assessment of simulated convective cell properties throughout their life cycles.
The resulting data set of convective cell objects is statistically analyzed in several ways. 1) Macrophysical properties, including the frequency, intensity, and area of high-impact weather situations, are compared. 2) The distribution into stratiform and convective precipitation is examined. 3) The ability of the model to reproduce statistical distributions of polarimetric signals is evaluated. 4) The results are related to the spatio-temporal development of the identified convective objects.

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**ID: 26, Oral Presentation**

## Comparing raindrop size distributions from the two-moment microphysics scheme of the ICON-RUC model with disdrometer observations

1) Sophie Löbel* (Deutscher Wetterdienst), 2) Nikolaos Antonoglou (Deutscher Wetterdienst), 3) Ulrich Blahak (Deutscher Wetterdienst), 4) Axel Seifert (Deutscher Wetterdienst), 5) Alberto de Lozar (Deutscher Wetterdienst), 6) SINFONY Team

The Rapid Update Cycle (RUC) has been developed to predict severe storms and especially-heavy rain falls over Germany. In order to forecast the precipitation more precisely, we have implemented a two-moment microphysics scheme, which predicts the number concentration of the hydrometeors in addition to their mass density. In the last two years we have found several cases where the predicted precipitation was too low, although the radar reflectivity showed realistic values. To investigate this behaviour, we started to compare more specific parameters of the model with more detailed precipitation observations.
Several stations in the Deutscher Wetterdienst measuring network include a disdrometer, which measures size and fall speed velocity of individual rain drops every minute. This enables the estimation of the drop size distribution, rain rate and mean diameter with high temporal resolution. Since all these parameters are also estimated by the two-moment microphysics scheme, a direct comparison between model and observations can provide a more specific insight into the problem.
First, observations of case days from the 2024 summer period with stratiform and convective conditions are evaluated and compared to short-time forecasts in the RUC setup. Specific areas around the disdrometers are used for this evaluation. We try to identify systematic model biases by comparing precipitation amount, the mean diameter and the droplet size distribution in the model and the disdrometers. Our aim is to understand these differences and evaluate possible model changes that can reduce these mismatches and thus improve precipitation forecasting.

**ID: 30, Oral Presentation**

## How important is turbulence for the formation of snow aggregation and riming in Arctic clouds?

1) Stefan Kneifel* (Meteorological Institute, Ludwig-Maximilians-Universität München), 2) Giovanni Chellini (LSCE/IPSL)

Turbulence in clouds is known to enhance particle collision rates which has been demonstrated for warm rain formation. It was often discussed and assumed that a similar effect should also exist for ice processes but so far strong observational evidence for this assumption was missing. We will present the results of a statistical analysis of a 15-month W and Ka band cloud radar dataset which allowed us for the first time to quantify the impact of turbulence on snow aggregation and riming in Arctic low-level mixed-phase clouds. We find that increasing Eddy Dissipation Rate (EDR, derived with mean Doppler velocity time series) correlated with larger snow aggregates revealed by dual-wavelength ratios. In temperature regimes more favourable for riming, higher EDR is associated with dramatically higher particle fall velocities (for same liquid water path category) indicative of markedly higher degrees of riming. The polarimetric observations at Ka band also indicate that ice fragmentation processes are also enhanced by turbulence especially in the temperature region where dendritic particles grow.

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**ID: 31, Oral Presentation**

## A detailed climatology of quasi-vertical profiles (QVPs) under stratiform conditions with identification and analysis of different microphysical processes (MPPs)

1) Tobias Scharbach* (Institute for Geosciences, Department of Meteorology, University of Bonn),
2) Silke Trömel (Institute for Geosciences, Department of Meteorology, University of Bonn)

We present a comprehensive climatology of QVPs of polarimetric variables based on the measurements of the X-band radar located in the city of Bonn in western Germany between 2013 and 2023. QVPs under stratiform conditions are selected, with particular attention paid to the signatures in the melting layer (ML) and the dendritic growth layer (DGL). Due to the unprecedented sample size and the inclusion of all seasons, this comprehensive climatology enables the verification of existing hypotheses with statistical evidence and a better understanding of MPP. Furthermore, this climatology provides a reference for the evaluation of numerical models and parameterization development. Statistical methods, e.g. correlation matrices, are used to analyze polarimetric variables in relation to the ML, DGL and the layer in between, e.g. the ML thickness or the maximum of the radar reflectivity factor ($Z_H$) within the DGL/ML. Hypotheses from former studies are tested, e.g. the seasonality of ML thickness or the ML amplitude, and to reveal dominating MPPs. To analyze the latter more precisely, so called microphysical fingerprints are utilized, in which the gradients of the polarimetric variables are used to identify different MPPs. For this purpose, existing techniques are used, e.g. the aggregation fingerprint, showing increasing $Z_H$ with simultaneous decreasing in the specific differential phase ($K_{DP}$) and the differential reflectivity ($Z_{DR}$) towards the ML. Additional innovative approaches are presented, such as the inclusion of the mean Doppler velocity from the birdbath scan in order to distinguish between aggregation and riming. In order to ensure the high significance of the climatology, a sufficiently precise calibration of the radar is guaranteed. $Z_H$ is calibrated using the relationship between $Z_H$ and $Z_{DR}$ in light rain. This method is highly dependent on an accurate calibration of the $Z_{DR}$. We highlight shortcomings that can occur when using the often preferred birdbath scan technique to correct $Z_{DR}$ and compare the corresponding results with an alternative calibration method that uses QVPs in light rain. The $Z_H$ offsets calculated with this technique are validated using both self-consistency relationships applying $K_{DP}$ and satellite information, demonstrating the suitability of this method.

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**ID: 43, Oral Presentation**

## Laboratory studies upon the fragmentation of ice particles due to collision

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The production of secondary ice in clouds is crucial for cloud microphysical processes but remains poorly understood. Collisions between ice particles are a key process potentially responsible for producing high concentrations of ice crystals. However, limited laboratory studies on ice collisions have constrained our ability to accurately model this phenomenon. In response, we conducted laboratory experiments in a walk-in cold chamber to investigate the fragmentation of ice particles due to collisions. Our experiments focused on collisions between graupel-graupel and graupel-snowflake particles. We collected and examined all fragments from graupel-graupel collisions under a microscope, while an in-house-developed holographic instrument captured ice fragments from graupel-snowflake collisions. From these data, we derived fragment number and size distributions, alongside their dependence on collision kinetic energy. We observed fragment counts reaching several hundreds, with size distribution peaks at 75 µm for graupel-graupel and 400 µm for graupel-snowflake collisions. Based on experimental data and theoretical frameworks, we propose new coefficients for parameterizing fragment production from ice-ice collisions. Ultimately, our project aims to integrate laboratory findings, radar observations, and numerical modeling to improve understanding of ice multiplication due to collisions.

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**ID: 51, Oral Presentation**

## The relationship between cloud thermodynamic structure and the properties of precipitation from cloud radar and disdrometer observations

1) Tom Gaudek* (TROPOS), 2) Johannes Bühl (Hochschule Harz, TROPOS), 3) Kevin Ohneiser (TROPOS), 4) Martin Radenz (TROPOS), 5) Patric Seifert (TROPOS)

Dominating precipitation formation processes vary in different climate regions. Cloud ice particles, which are involved in most of these processes, are usually formed at the uppermost cloud layer. As underlying formation processes strongly depend on temperatures of the ambient air, cloud top temperatures may indicate the initial formation process of precipitating hydrometeors. Therefore, several temperature regimes can be defined and assigned to dominant formation processes. Warm-rain formation, for example, can be allocated to cloud top temperatures above 0°C. Between 0°C and -25°C, freezing processes with contributing liquid water such as immersion or contact nucleation may occur additionally. Below around -30°C, deposition freezing may happen as well, and below around -40°C, cloud ice can also form homogeneously.

The goal of this study is to connect precipitation events on the ground with the ambient temperature at their area of formation at the cloud top in order to retrieve a statistical overview on the relevance of the abovementioned key ice nucleation processes for the precipitation budget. Exemplarily, a long-term dataset of cloud radar and disdrometer observations of the mobile Cloudnet station LACROS (Leipzig Aerosol and Cloud Remote Observations System) was used for this study. Temperature information were obtained from the ECMWF IFS model, provided via Cloudnet. Each precipitation event detected by the disdrometer is assigned a cloud top height from the radar measurements. For this purpose, the application of a fallstreak algorithm was applied as the cloud top height detected by radar may change between the formation of the hydrometeor and its detection on the ground. The fallstreak propagation is based on the reflectivity values of the single radar bins. The method presented in this study was applied to a multi-year dataset which allows to create statistics of dominating cloud top temperature regimes during precipitation formation over contrasting sites such as Leipzig, Germany, Limassol, Cyprus, and Punta Arenas, Chile.

The results show that precipitating clouds can be categorized into different cloud top temperature regimes which can be associated with different precipitation formation processes. If the method is applied to datasets of stations in different climate zones, potential results may reveal varying dominating formation processes. Therefore, this method may have great potential to contribute to cloud research in a global context, for example, by evaluating cloud models. Moreover, the frequency of precipitation formation events under different aerosol and dynamics conditions can be investigated, if the method is extended.

**ID: 53, Oral Presentation**

## ROTOЯ – Constraining the role of warm rain processes for cloud amount and cloud organization in the trades

1) Raphaela Vogel* (University of Hamburg), 2) Nils Antary (Max Planck Institute for Meteorology, Hamburg, University of Hamburg), 3) Clara Bayley (Max Planck Institute for Meteorology, Hamburg), 4) Nils Niebaum (University of Hamburg), 5) Florian Poydenot (University of Hamburg), 6) Nina Robbins-Blanch (University of Hamburg), 7) Jan Kazil (NOAA Earth System Research Laboratory, ESRL), 8) Mampi Sarkar (University of Houston), 9) Zeen Zhu (Brookhaven National Laboratory)

Warm rain processes like rain evaporation, downdrafts, and cold pools play an important but poorly understood role in controlling cloud amount and organization in the trade-wind regions. Evaporatively-driven cold pools both enhance cloudiness by triggering arcs of new clouds at the gust front, and reduce cloudiness inside the cloud arcs by suppressing surface-forced convection. Likewise, cold pools were shown to both organize and disorganize shallow convection in high-resolution modelling studies. Unfortunately, we don't know which of the contrasting effects of cold pools on cloud amount and organization dominates. Here we argue that these knowledge gaps are tightly linked to a lack of robust longterm rain process observations and the fact that we don't know if state-of-the-art models with their crude microphysical parameterizations have skill in simulating the rain processes.

In the ERC starting grant project ROTOЯ (Rain and cloud Organization in the Trades using ObseRvations and models) we aim to overcome these problems by (1) creating a multi-year dataset of rain evaporation, downdrafts and cold pools by applying new remote sensing techniques to observations from the Barbados Cloud Observatory and the EUREC4A and ORCESTRA field campaigns, and (2) by performing & evaluating large-eddy simulations on O(100 km) domains using Lagrangian Superdroplet microphysics. In this talk, we present our strategy and discuss initial results of the role of microphysical complexity in controlling rain evaporation rates in an observationally-constrained 1D rainshaft model.

**ID: 55, Oral Presentation**

## Ground-Based Observations of Secondary Ice Production: A Case Study Showing Droplet Fragmentation during Refreezing Rain

1) Nils Pfeifer (Leipzig Institute for Meteorology (LIM), Leipzig University), 2) Susan Hartmann (TROPOS), 3) Bernd Mom (University of Helsinki), 4) Dmitri Moisseev (University of Helsinki), 5) Maximilian Maahn* (Leipzig Institute for Meteorology (LIM), Leipzig University)

The discrepancy between the concentration of ice nucleating particles and ice in the atmosphere, which can reach up to several orders of magnitude, indicates the importance of secondary ice formation and has led to the suggestion of several secondary ice processes (SIPs). Despite their recognized importance, SIPs remain insufficiently quantified and parameterized in atmospheric models. Some SIPs are entirely theoretical, while others have been demonstrated in laboratory settings. One SIP is droplet fragmentation, where the freezing of liquid droplets leads to the formation of small ice splinters as the droplets shatter. Laboratory studies indicate that this process operates effectively over a broad temperature range, particularly with larger droplets. However, like many secondary ice processes, it is challenging to observe and quantify in natural environments.

Ground-based in situ precipitation measurements provide a viable method for studying these phenomena, offering direct measurements over extended periods with minimal disruption. This approach captures a wide variety of microphysical scenarios and facilitates real-time monitoring of changes in hydrometeor characteristics.

This talk presents a case of refreezing rain recorded in Hyytiälä, Finland, which indicated secondary ice production through droplet fragmentation. An analysis using ground-based in-situ data from the third generation of the Video in Situ Snowfall sensor, combined with the spectral linear depolarization ratio from W-band cloud radar measurements supported this hypothesis. Multiple modes of droplet fragmentation that were identified through in situ imagery, accompanied by a significant increase in ice particle concentration will be shown. Further, we will quantify and characterize the hydrometeors affected by freezing and shattering, as well as SIP particles produced during the event.

**ID: 58, Oral Presentation**

## DISDRODB: a global data base of raindrop size distribution observations

1) Gionata Ghiggi* (EPFL), 2) Anne-Claire Billault-Roux (EPFL), 3) Kim Candolfi (EPFL), 4) Leo Pillac-Mage (EPFL), 5) Christine Unal (Delft University of Technology), 6) Marc Schleiss (Delft University of Technology), 7) Remko Uijlenhoet (Delft University of Technology), 8) Tim Raupach (UNSW), 9) Alexis Berne (EPFL)

The drop size distribution (DSD) describes the number and size of raindrops in a volume of air. Knowledge of the DSD is key to model the propagation of microwave signals through the atmosphere (crucial for telecommunication and radar remote sensing), to improve microphysical schemes in numerical weather prediction models, and to understand rain-related land surface processes (rainfall interception, soil erosion).
Despite its importance, the spatial and temporal variability of the DSD remains poorly understood. This has motivated scientists all around the globe to deploy DSD recording instruments known as disdrometers, in order to collect DSD observations in various climatic regions. However, only a small fraction of these data is easily accessible by the research community. Data are stored in disparate formats with poor documentation, making them difficult to share, analyze, compare and re-use. Additionally, very limited software is currently publicly available for DSD processing.
This presentation introduces the DISDRODB project, which addresses these challenges by establishing a decentralized disdrometer remote data archive, a public station metadata repository hosted on GitHub, and an open-source Python software for retrieving raw station data and generating quality-controlled analysis-ready L1 and L2 products.
Disdrometer data from hundreds of public stations from various institutions (including NASA, NCAR, ARM, NCEP, NERC, INPE, EPFL, TU Delft) are used to characterize global DSD variability, derive rainfall scaling laws at short spatio-temporal scales, and simulate radar polarimetric variables across multiple frequency bands.
By consolidating and mobilizing existing data archive, the envisioned publicly-accessible global database of standardized disdrometer measurements and derived products aims to accelerate and advance precipitation research as well as foster international collaborations.

**ID: 63, Oral Presentation**

## Linking Ice-Phase Microphysics to Raindrop Characteristics, and Extreme Rainfall in a Deep Convection Event in Eastern China

1) Kun Zhao* (Nanjing University), 2) Gang Chen (Nanjing Joint Institute for Atmospheric Science), 3) Hao Huang (Nanjing University), 4) Zhengwei Yang (Nanjing University)

In this study, we examine the evolution of ice-phase microphysics [polarimetric radar signatures and identified graupel and hail (GH) (hereafter, GH) distributions] and raindrop characteristics [drop size distribution (DSD) and rainfall intensity] in a extreme rainfall produced by convection during the Meiyu period in Eastern China. The results showed in the convection, strong updraft favored the lifting of raindrops to the mixed-phase region to form abundant supercooled liquid water and GH. Meanwhile, raindrop characteristics are found to be deeply affected by the GH distribution condition, heavy rainfall (rain rate $> 20$ $\mathrm{mm\,h^{-1}}$) is basically contributed by convective samples with GH identified aloft. As GH height rises, number concentration and mean size of raindrops increase accordingly, leading to the growth of rainfall intensity. Extreme rainfall (rain rate $> 100$ $\mathrm{mm\,h^{-1}}$) is majorly induced by deep convection with hail or widespread (over 10 km level) graupel, melting of the abundant highly-rimed particles plays a dominant role in generating high concentration raindrops. By revealing the link between GH distribution conditions and raindrop characteristics, the study helps to understand the specific role of ice-phase processes to the formation of low-level raindrops in deep convection.

**ID: 64, Oral Presentation**

## Study on Microphysics of Stratiform Precipitation Based on Dual-Polarization Radar and Airborne Observations

1) Hao Huang* (Nanjing University), 2) Kun Zhao (Nanjing University), 3) Xiangfeng Hu (Key Laboratory of Radar Meteorology and State Key Laboratory of Severe Weather), 4) Guifu Zhang (University of Oklahoma), 5) Yinghui Lu (Nanjing University)

Understanding the microphysical properties of stratiform precipitation is crucial for advancing weather prediction models and deepening our understanding of atmospheric processes. This study integrates advanced techniques in dual-polarization radar and airborne observations to conduct a comprehensive analysis of stratiform precipitation microphysics. First, a variational approach to optimize drop size distribution (DSD) retrieval, attenuation correction, and rainfall estimation using polarimetric radar measurements (horizontal reflectivity factor $Z_H$), differential reflectivity $Z_{\mathrm{DR}}$, and differential phase shift $\Phi_{\mathrm{DP}}$ is used. Our approach employs radial B-spline filtering and azimuthal Kalman filtering to ensure the spatial continuity of rain and mitigate random errors in $Z_{\mathrm{DR}}$ and $\Phi_{\mathrm{DP}}$. Validation includes simulated experiments and real-case observations from mobile C-band and operational S-band polarimetric radars in South China, demonstrating that our method achieves more accurate attenuation correction and rainfall estimates compared to conventional methods. Furthermore, we investigate microphysical structures and processes in precipitating stratiform clouds using joint observations from an aircraft and the optimized estimates from an X-band polarimetric radar. A case study conducted over North China on May 21, 2018, reveals enhancements in $Z_{\mathrm{DR}}$ and specific differential phase $K_{\mathrm{DP}}$ above 7 km altitude, indicating the presence of dendrites and platelike ice crystals. Above the melting layer (ML), aggregation processes increase $Z_H$ and decrease $Z_{\mathrm{DR}}$, as confirmed by aircraft observations showing an increase in volume-weighted mean diameter ($D_m$) and a decrease in total number concentration ($N_t$). Within the ML, melting particles exhibit complex behaviors, with aggregation dominating the upper part and breakup processes prevailing in the lower part, influencing particle size and concentration. Below the ML, microphysical processes exhibit minimal variation with altitude, indicating a near balance in nearly saturated air. These findings significantly contribute to our understanding of stratiform precipitation microphysics and provide valuable insights for improving microphysical parameterization in numerical weather prediction models, emphasizing the integration of advanced radar techniques and airborne observations.

**ID: 76, Oral Presentation**

## Can ice-ice fragmentation explain the typical radar signatures in the dendritic growth layer? An investigation combining polarimetric multi-frequency radar observations wth Lagrangian Monte-Carlo particle modeling

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The dendritic growth layer (DGL), centered around -15°C, plays a key role in the formation of precipitable ice and snow particles. Particle growth by vapor deposition and subsequent aggregation are strongly enhanced in the DGL. As a result, multiple radar observables display distinct features related to the plate-like particle shapes as well as rapid formation of aggregates. Specifically, enhanced ZDR and KDP are frequently interpreted as the depositional growth of plate-like particles and the increase in DWR as aggregation. However, radars only observe the effect of ice microphysical processes (IMPs) on the observed particle distribution, not the IMPs themselves. Therefore, especially the origin of the plate-like particles which might cause enhanced ZDR and KDP are not fully understood. Common hypotheses include ice crystals which sediment into the DGL from colder temperatures, primary nucleation due to an updraft and local activation of INP and secondary ice production (SIP), possibly ice-ice collisional fragmentation. In this contribution, we combine zenith triple-frequency (X, Ka, W-band) and slant-viewing W-band spectral polarimetric radar observations with Monte-Carlo Lagrangian particle modeling to shed light on the typical DGL radar signatures. The Monte-Carlo particle model McSnow allows us to describe and investigate IMPs on the detailed particle level. Recently, a habit prediction scheme which simulates the evolution of ice crystal shape and density has been implemented. Ice habit, particle size, density and fall velocity are core information for radar forward simulations, facilitating the comparison with radar observations and allowing to link the radar observations to specific IMPs. New laboratory studies on ice-ice collisional fragmentation allowed us to implement a fragmentation scheme in McSnow. To make full use of the rich information content of the McSnow simulations, a new radar forward operator has been developed. The forward operator is based on DDA calculations of more than 1500 ice crystals with varying habits, as well as 600 aggregates with varying degrees of riming. McSnow simulations suggest that the particles responsible for the increase in ZDR need to be produced within the DGL, either via primary or secondary ice production. The simulations further suggest that the increase in KDP at -15°C might be linked to fragmentation. Surprisingly, our study also suggests that the increase in KDP is not only caused by ice crystals, aggregates also have a significant contribution to KDP.

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**ID: 79, Oral Presentation**

## From Cloud Tops to Surface: Statistical Insights into Stratiform Microphysics over Germany and Türkiye

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This study presents a statistical analysis of stratiform precipitation events across Germany and Türkiye using quasi-vertical profiles (QVPs) derived from three C-band radars in Germany and five C-band radars in Türkiye, covering the time period from 2015 to 2020. The dataset allows for an in-depth examination of microphysical processes at all height levels from the dendritic growth layer, where precipitation is generated, to the melting layer and down to the surface. Comparative analysis highlights notable regional differences in precipitation profiles and microphysics, linked to the distinct climates of Germany and Türkiye. For instance, QVPs from Türkiye show higher values of specific differential phase KDP in the dendritic growth layer with deeper and colder cloud tops compared to Germany, linked to greater ice water content in Turkish clouds. Additionally, two radars in Türkiye exhibit decreasing reflectivity ZH from the melting layer to the surface while maintaining stable differential reflectivity ZDR, indicating evaporation effects, consistent with a drier climate region. A riming detection algorithm further reveals enhanced riming frequency in Germany compared to Türkiye, with the exception of a Turkish coastal radar at low altitude. The latter shows dominant riming processes in up to 30% of the events, similar to German observations. Interestingly, we observe a correlation between increased riming frequency and lower cloud-top heights, while no relationship is found between riming frequency and melting layer thickness. This analysis provides new insights into the varying dominant microphysical processes in stratiform precipitation and different climate regimes and enables in the next step an in-depth evaluation of numerical weather prediction models.

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**ID: 80, Oral Presentation**

## Detailed spectral-bin microphysics simulations of primary ice formation in artificially seeded supercooled stratus clouds

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The PolarCAP project aims to better understand the interplay between aerosol and cloud-microphysical processes by investigating the evolution of the ice phase under slightly supercooled conditions ($T > -10$ °C) within a thermodynamically and aerosol-controlled environment, employing radar polarimetry, holographic imagery and spectral-bin modelling. In collaboration with the CLOUDLAB project at the ETH Zurich, PolarCAP investigates the development of an artificially initiated ice phase within supercooled stratus clouds. Utilising cloud seeding with silver iodide, CLOUDLAB initiates the freezing process of cloud droplets. The subsequent evolution is monitored using in-situ measurements and ground-based cloud remote sensing tools. The collaboration has yielded a unique dataset, incorporating observations from the Leipzig Aerosol and Cloud Remote Observations System (LACROS) and observations from CLOUDLAB in tandem with data from the cloud-resolving spectral-bin microphysics model COSMO-SPECS. We present a comparative evaluation between observational data and simulations of the spectral-bin model COSMO-SPECS (CS) featuring an artificial particle source. A multitude of ensemble CS model runs were performed on two different mesh sizes, with horizontal resolution of ∼400 m and ∼100 m in various configurations. First, we demonstrate the CS model's ability to reproduce observed cloud responses, providing insights into ice nucleation and growth processes, in particular the Wegener-Bergeron-Findeisen (WBF) process. During the seeding experiments, observations show simultaneous decreases in cloud droplet concentrations alongside increases in ice crystal concentrations, including periods where cloud droplets were entirely depleted. Our findings suggest that significant amounts of flare INP are required to replicate observed ice crystal concentrations and cloud droplet reductions. This could indicate that the model scheme may be unsuited for deriving immersion INP concentrations from flare particle emissions. Second, the measured ice crystal sizes and growth rates, are compared to the CS output. This comparison revealed discrepancies in ice crystal size distributions, highlighting potential model biases due to parametrizations of ice crystal growth. Furthermore, the comparison revealed insights into the importance of spatial resolution of the CS model.

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**ID: 111, Oral Presentation**

## Investigation of aerosol effects on precipitation initiation processes in the alternately clean and aerosol-laden environment of New Zealand Aotearoa

1) Patric Seifert* (Leibniz Institute for Tropospheric Research (TROPOS)), 2) Heike Kalesse-Los (Leipzig University), 3) Martin Radenz (Leibniz Institute for Tropospheric Research (TROPOS)), 4) Tom Gaudek (Leibniz Institute for Tropospheric Research (TROPOS)), 5) Albert Ansmann (Leibniz Institute for Tropospheric Research (TROPOS)), 6) Andreas Macke (Leibniz Institute for Tropospheric Research (TROPOS)), 7) Adrian McDonald (University of Canterbury), 8) Guy Coulson (The Air Quality Collective)

Down to temperatures of -38°C the primary formation of liquid or frozen hydrometeor requires the availability of aerosol particles, which act either as cloud condensation nuclei (CCN) or ice nucleating particles (INP). An actual quantification of the influence which perturbations in the aerosol load do have on a clouds' microphysical structure and its evolution toward precipitation is nevertheless still hardly achievable. Strong need is given to improve this lack of scientific understanding, because state-of-the-art physical representations of cloud processes show a lack of accuracy especially in regions where the aerosol load deviates from the general mean.
It is scope of the project ACADIA (Aerosol-Cloud-rADiation-interaction over Aotearoa) to conduct a unique contrast study which is about to disentangle the relationships between aerosol load, cloud and precipitation processes, and the radiation budget, based on a 1-year multi-site field campaign on the South Island of New Zealand Aotearoa. ACADIA, which is a joint project of Leibniz Institute for Tropospheric Research (TROPOS) and the Leipzig Institute for Meteorology (LIM) of the University of Leipzig, will exploit the alternation of Australian and clean Southern-Ocean dominated air masses and the transformation processes during transport over 400 km of landmass of the South Island of New Zealand to disentangle the role of aerosol load on the microphysical and radiative properties of clouds and their evolution. TROPOS and LIM will place extensive ground-based remote sensing equipment to the sites of Invercargill and Tawhaki, respectively. The key instrumentation consists of multi-wavelength cloud Doppler polarization radar and lidar systems with polarization, fluorescence and Doppler capabilities. ACADIA is scheduled to take place from August 2025 to August 2026 and will be embedded in a series of already scheduled field experiments, which are implemented under the umbrella of the goSouth-2 consortium. Those include deployments of the HALO aircraft, the research vessel Sonne, and the mobile ground-based remote sensing infrastructure LACROS of TROPOS. Contextualization with spaceborne profiling lidar and radar observations from the EarthCARE satellite and aerosol-permitting model simulations will take place, in addition.
The presentation will focus on three subjects. We will provide an overview on recent findings about the role of aerosol perturbations on precipitation initiation processes. We will motivate the location of New Zealand for aerosol perturbation studies. Finally, the ACADIA project and the partner projects which are scheduled to take place within the goSouth-2 consortium will be introduced and the possibilities for additional collaborations will be elaborated.

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**ID: 25, Poster**

## Lack of INP and precipitation in supercooled stratus clouds over the Swiss Plateau might be explained by upwind INP activation and removal

1) Kevin Ohneiser* (TROPOS), 2) Veronika Ettrichrätz (Leipzig Institute for Meteorology (LIM), Leipzig University), 3) Christopher Fuchs (ETHZ), 4) Tom Gaudek (TROPOS), 5) Hannes Griesche (TROPOS), 6) Anna Miller (ETHZ), 7) Max Maahn (Leipzig Institute for Meteorology (LIM), Leipzig University)

Ice Formation at slightly supercooled temperatures of -10°C and above is an important research topic – especially the understanding of ice formation in INP-limited scenarios and the secondary ice formation pathways as well as their interaction with (thermo-)dynamics and aerosol conditions are not completely understood.
Slightly supercooled low-level stratus clouds over the Swiss Plateau are often found to be ice-free which is in contrast to comparable stratus clouds over Germany. The lack of ice and precipitation in these clouds might favour their longevity. Following our hypothesis, the lack of ice may be the result of INP activation and removal between Southern Germany and the Swiss Plateau in supercooled northeasterly wind conditions. We conducted INP measurements at Hohenpeißenberg (Germany) and Eriswil (Switzerland) to test our hypothesis. We found an INP contrast between both places in northeasterly winds and supercooled conditions. During stratus conditions with northeasterly winds but temperatures above freezing no INP contrast was observed which is in line with the hypothesis because the INP cannot be activated at these temperatures. The remaining very limited INP reservoir between -7 and -12°C was of biogenic origin.
Within the PolarCAP project, the remote sensing equipment of LACROS (Leipzig Aerosol and Cloud Remote Observations System) was installed in Eriswil, Switzerland during two winter campaigns between 2022 and 2024. In collaboration with ETH Zurich and DWD INP samplers were located in Eriswil and also around 300 km upwind at Hohenpeißenberg.
This contribution focuses on the evaluation of the hypothesis that there is an observable depletion of INP concentration and associated ice formation efficiency over a horizontal range of around 300 km between the downwind edge and the observations site during shallow supercooled stratus conditions.

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**ID: 41, Poster**

## Quantifying the Underestimation of Rainfall by Rain Gauge Networks: Significance, Implications and Recommendations

1) Ruth Dunn* (Newcastle University), 2) Hayley Fowler (Newcastle University), 3) Amy Green (Newcastle University), 4) Elizabeth Lewis (The University of Manchester)

Accurately measuring precipitation is notoriously difficult. Traditionally, precipitation at the Earth's surface is measured using catching-type rain gauges, and many countries have national networks and historical records spanning multiple decades. Large datasets of such longevity enable the study and detection of non-stationarity trends and extremes, providing a means of investigating climate change and its impacts from either natural or anthropogenic forcings. While remote sensing techniques are becoming increasingly popular, indirect measurements often rely on rain gauges for calibration and validation, underscoring the continued importance and relevance of rain gauge data. Unfortunately, precipitation data collected by rain gauges is infamously unreliable due to a multitude of errors. Improving the accuracy of rain gauge records will enable us to better observe and understand climate variability and climate change effects on precipitation, facilitating improved design storm estimation and contributing to the construction of more effective and resilient infrastructure systems. Additionally, as rainfall data serves as the primary input for most hydrological models, enhancing the accuracy of this data will result in more reliable flood simulations, aiding in the identification and mitigation of flood risks, and fostering a greater understanding of the mechanisms operating within a catchment. Furthermore, if applied at real-time, more accurate rainfall data will also aid in the effective monitoring of and response to evolving situations. This research aims to investigate rain gauge undercatch in a British context, initially utilising existing data from catchments densely populated with rain gauges, and subsequently new data from rainfall simulator experiments. The primary objectives include creating a comprehensive summary of key rain gauge errors at both the gauge and catchment scale, identifying the applications most sensitive to undercatch, and establishing the relationship between the extent of undercatch, rain gauge type, and meteorological conditions. Through this investigation, a correction methodology will be developed to enhance the accuracy and reliability of both historic and future rainfall datasets. Moreover, the study will establish the contexts where the application of this correction methodology is most crucial. The outcomes of this research hold significant implications for understanding climate change effects, improving flood simulations, and designing resilient infrastructure. By addressing the challenges associated with rain gauge data accuracy, this study contributes to greater climate awareness and more informed decision-making.

**ID: 17, Poster**

## Development and Assessment of Instruments for Rainfall Microphysics Observations

1) Firat Testik* (University of Texas at San Antonio)

Rainfall microphysics plays a fundamental role in various applications, including remote sensing and precipitation estimations, meteorological and hydrological modeling, atmospheric telecommunications, and opportunistic sensors for precipitation. Consequently, ground-level and above-ground rainfall microphysics observations are crucial for a wide range of precipitation-related applications. This study introduces optical-type disdrometers developed in the author's laboratory, along with unique microphysics observations collected by these disdrometers. Additionally, it presents assessments of the measurement accuracies of a widely used commercial disdrometer (OTT-Parsivel2) and rain gauge (OTT-Pluvio2). Our efforts involved both indoor and outdoor laboratory tests. Indoor tests utilized water drop generators to evaluate the measurement capabilities of the meteorological instruments. These results were instrumental in developing software for the new instruments and identifying measurement principles and relevant calculations for the commercial instruments. Outdoor tests verified the indoor findings and demonstrated the instruments' measurement capabilities during actual rainfall events. This presentation will provide an overview of the new disdrometers developed and the findings for the commercial disdrometer and rain gauge. Furthermore, it will showcase unique field observations obtained through these innovative technologies.

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# Session 2.B: Enhancing process understanding. Model parameter estimation

**ID: 65, Oral Presentation**

## Exploiting polarimetric radar observations to improve the ICON-D2 2-moment microphyiscs

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Polarimetric radar operators such as EMVORADO (Efficient Modular VOlume scan RADar Operator) enable the direct comparison of numerical weather simulations with radar observations in the polarimetric observation space. Additionally, microphysical retrievals are the appropriate way to conduct a synergistic comparison in model space. Our objective is an in-depth evalutation of the 3-dimensional representation of hydrometeors in ICON-D2 employing both strategies.
ICON-D2 with the two-moment microphysical scheme from Seifert-Beheng shows, similar to other numerical weather models, a tendency towards excessive riming and an overproduction of graupel. As a consequence, also oversized drops are simulated below the melting layer. In order to converge ICON simulations and according synthetic radar variables simulated with the EMVORADO to the actual radar observations, model evaluation and model parameter adjustment has been applied in an iterative procedure. This implies several experiments with adjusted microphysical parameters of ICON (e.g. sticking efficiencies, riming efficiencies, terminal velocities, shedding parameters) together with improvements in the melting scheme of EMVORADO. Among the challenges is the development of one universal melting scheme for both large-scale stratiform precipitation and convective thunderstorms. This study investigates the representation of hydrometeors in ICON-D2 and the performance of EMVORADO in different weather situations, in different seasons and for the whole German C-band radar network.
Until now, significant improvements have been achieved, e.g. reduced graupel production and mean droplet sizes that are more consistent with the radar measurements. In convective situations, we are able to identify synthetic/simulated columns of enhanced differential reflectivity, ZDR columns, although with smaller ZDR values compared to observations. First results show too much graupel above the melting layer dominating the ZDR signal but only small raindrops are transported upwards. The opposite is true for the areas below the cores of convective storms, where the formation of too large raindrops is apparent.

### Acknowledgements

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**ID: 75, Oral Presentation**

## Predicting Realistic Snow Shape for Improved Polarimetric Radar Simulations

1) Soumi Dutta* (Institute of Geophysics and Meteorology, University of Cologne), 2) Davide Ori (Institute of Geophysics and Meteorology, University of Cologne), 3) Jana Mendrok (Deutscher Wetterdienst), 4) Ulrich Blahak (Deutscher Wetterdienst), 5) Christoph Siewert (Deutscher Wetterdienst), 6) Axel Seifert (Deutscher Wetterdienst), 7) Leonie von Terzi (Meteorological Institute, Ludwig-Maximilians-Universität in Munich), 8) Stefan Kneifel (Meteorological Institute, Ludwig-Maximilians-Universität in Munich)

Radar Forward Operators (RFOs) bridge the gap between the physical properties of clouds and precipitation and the observed radar quantities. A significant source of uncertainty in RFOs arises from assumptions about the scattering properties of frozen and mixed-phase hydrometeors. Polarimetric RFOs often use simplified, homogeneous shape models. These cannot reflect the multifaceted structure of snow, which, however, significantly affects the polarimetric radar properties. This study explores the use of Discrete Dipole Approximation (DDA) scattering models to incorporate realistic shapes of snow particles to overcome this limitation. However, it is well-known that snow particles appear in a vast variety of habits, and it is not straightforward to assume one shape that fits it all. Conversely, operational weather models do not provide sufficient constraints to model ice particle shapes that unambiguously represent the generic internal ice microphysical assumptions (i.e., mostly just mass-size relation). The present study uses a cascade of progressively more detailed models that explicitly predict the shapes of ice crystals and snow aggregates to be used to model their radar multi-frequency (C, X, Ka, and W-band) polarimetric signature with DDA.
The core of the modeling framework is the shape-predicting, semi-Lagrangian, cloud model McSnow that takes the ICON atmospheric state and simulates the evolution of the microphysical properties of cloud and precipitation particles (mass, size, aspect ratio, rime fraction, melted fraction) as well as the number of monomers composing snow aggregates. By tracking the sequence of aggregation events that originated each aggregate, it is possible to reconstruct the properties of each monomer. This information can be used to simulate realistic aggregate shapes using a physically based aggregation model. This model reproduces the collision process with great detail and provides snowflake shapes that match the properties of the snowflake as they are modeled by McSnow.
Key questions of the present study that enhance the process understanding of cloud microphysics include: (1) To what extent do multi-frequency and polarimetric radar signatures of snow depend on the detailed shapes of the aggregates? (2) Can DDA improve over the T-matrix and provide a reliable representation of the scattering properties of snowflakes for use in RFOs? (3) Can a snow particle model be identified that represents polarimetric radar properties of snow for most weather scenarios, and what uncertainties are inherited in such generalized assumptions?

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**ID: 66, Oral Presentation**

## On the geometry and growth of aggregate snowflakes

1) Fabian Jakub (Deutscher Wetterdienst), 2) Axel Seifert* (Deutscher Wetterdienst), 3) Christoph Siewert (Deutscher Wetterdienst), 4) Leonie von Terzi (Meteorological Institute, Ludwig-Maximilians-Universität in Munich)

It is often said that no two snowflakes are alike. This usually refers to dendritic crystals, which can develop complicated and therefore unique branches. Most snowflakes in the atmosphere are not dendrites, but aggregates of primary crystals such as plates, dendrites or needles (also called monomers). Each aggregate is unique because the size, shape, collision angles, and overlap of the monomers are random. Earlier work has shown that aggregate snowflakes show a fractal scaling behaviour for large monomer numbers (also called cluster size). Nevertheless, there is a large variability of aggregate snowflake geometry. Given a certain snowflake mass and monomer number, the observable variables such as maximum dimension, aspect ratio, and terminal fall velocity can vary greatly. To understand and parameterize snowflake geometry, we have generated several million aggregate snowflakes with an aggregation model. This dataset allows us to parameterize the joint probability distributions of maximum dimension, aspect ratio, and cross-sectional area for aggregate snowflakes. These probability distributions have been implemented in the Monte-Carlo super-particle model McSnow as a stochastic parameterization of snowflake geometry. This allows us to investigate the effect of snowflake variability on snowflake growth. The collision kernel is affected by the geometry itself and by the variability in terminal fall velocity caused by the different geometries. Hence, by taking into account the variability in snowflake geometry two snowflakes with the same mass can indeed collide, because they end up having different terminal fall velocities. Similar to considering turbulence effects in the collision kernel, this leads to a faster growth of aggregates. McSnow can already predict the habit of primary crystals using a spheroid model. This habit information can now be propagated to the aggregates. With the new stochastic snowflake model, McSnow can distinguish between aggregates of plates, aggregates of needles, and mixture aggregates. To investigate the impact of the stochastic snowflake model on (polarimetric) radar quantities, we need to consistently forward simulate the model output. For this we have used DDA on representative aggregates from the aggregate database, generating a large scattering database. First results indicate that contrary to previous forward simulations using soft spheroid models such as the T-matrix, aggregates contribute significantly to the specific differential phase shift KDP. Also, the variability of snowflake geometry leads to a broadening of the Doppler spectra. The latter are often too narrow in numerical cloud models with simplified snowflake assumptions.

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**ID: 52, Oral Presentation**

## A gravity-driven inverse cascade controls the size distribution of raindrops

1) Florian Poydenot* (Universität Hamburg, Laboratoire de Physique de l'Ecole Normale Supérieure (LPENS) France), 2) Bruno Andreotti (Laboratoire de Physique de l'Ecole Normale Supérieure (LPENS), Paris)

Cloud droplets grow via vapor condensation and collisional aggregation. Upon reaching approximately ≈100 µm, their inertia allows them to capture smaller droplets during descent, initiating rain. Here, we show that raindrop formation is not primarily governed by gravity or thermal diffusion, but by a critical range of drop sizes (3—30 µm) where collisions are largely ineffective and controlled by van der Waals and electrostatic interactions. We identify several pathways to rain. The coalescence pathway, which is slow, involves the broadening of the drop size distribution across the 3—30 µm low-efficiency gap through collisions, until enough large individual droplets achieving efficient collisions have formed. The turbulence pathway relies on air turbulence to bring the droplets together at an increased rate, but we show that this pathway is unlikely. For all dynamical mechanisms, we demonstrate that the initiation time for rainfall occurs at the crossover between the broadening of the drop size distribution and the emergence of individual droplets large enough to trigger the onset of the rainfall cascade. We propose a reductionist, spatially homogeneous and stationary cloud model, the theoretical treatment of which is based on an analogy with the turbulent energy cascade. We show that this cloud is not just a simple idealisation, but can be used to describe in detail observations of drop size distributions, both in clouds and in rain on the ground, and their links with the various growth mechanisms. This surprising agreement opens up new avenues for the parameterisation of cloud microphysics in atmospheric models.

**ID: 132, Oral Presentation**

## Simulation of convective precipitation in idealized and realistic supercell cases with the P3 cloud microphysics scheme in ICON

1) Marco Wurth* (IMKTRO - KIT), 2) Corinna Hoose (KIT), 3) Jason Milbrandt (Meteorological Research Division, ECCC), 4) Melissa Cholette (ECCC), 5) Hugh Morrison (NCAR)

Many uncertainties exist in the parameterization of microphysical processes in bulk schemes. The Predicted Particle Properties (P3) bulk scheme lets ice particles seamlessly evolve in a more natural way without the necessity of conversion between pre-defined ice-phase categories. Therefore microphysical processes like riming, which is the key process in hail production, can be formulated more realistically. In this study the P3 scheme was coupled to the Icosahedral Nonhydrostatic model (ICON) via the new Community Interface ComIn. The recent version 5 of P3 (Cholette et al., J.A.M.E.S, 2023) is able to run with three moments and multiple categories for the ice phase, allowing the simulation of hail without numerically diluting it in areas of new ice nucleation. The correct physics-dynamics coupling behavior was tested comparing P3 with ICON's traditional 2-moment bulk scheme in an idealized splitting supercells testcase. The different approaches in handling the condensation of both schemes were explored, including their impacts for different cloud condensation nuclei (CCN) concentrations. Further, a realistic case study of isolated supercells on 10 Nov 2018 in Central Argentina from the RELAMPAGO-CACTI campaign was set up with ICON and both schemes at storm-resolving resolutions. A custom CCN parameterization was developed using aerosol measurements of CACTI to constrain this sensitivity pathway. Finally a forward operator is used to compare polarimetric simulated fields to polarimetric radar measurements of RELAMPAGO. Sensitivities to perturbations of microphysical parameters in the P3 scheme will be shown.

**ID: 36, Oral Presentation**

## Preparing the two-moment microphysical scheme for operational forecasts using radar and satellites

1) Alberto de Lozar* (Deutscher Wetterdienst), 2) Ulrich Blahak (Deutscher Wetterdienst), 3) Sophie Löbel (Deutscher Wetterdienst), 4) Leonhard Scheck (Deutscher Wetterdienst), 5) Axel Seifert (Deutscher Wetterdienst)

The Deutscher Wetterdienst has recently introduced a new Rapid Udpate Cycle (RUC) for a seamless transition between Nowcasting (a pure radar product) and Numerical Weather Prediction (NWP). The two-moments scheme (Seifert and Beheng 2006) produces significantly more realistic reflectivities than the currently operational one-moment scheme, thus allowing for a smooth transition between Nowcasting and NWP. The challenge in the last years has been to prepare the two-moments scheme, which has been previously mostly used for research, to be employed for operational weather forecasts.
The two-moment scheme includes evolution equations for the number concentration of the different hydrometeors. This means that the mean size of each hydrometeor in the model is known, which allows for more-physical assumptions in the parameterized processes. The challenge is that many of the involved parameters, such as sticking efficiencies, ice nuclei concentrations or sedimentation velocities, are to a large degree unknown. It is not only that there have been insufficient laboratory experiments related to these processes (quite frequent), but also that the model assumptions are too simple to capture a more-complex reality. This means that many of the microphysical parameters need to be tuned.
Knowing the size of each hydrometeor in the model also provides a key advantage when considering forward operators, especially radar and satellites. For example, few very large graupel particles produce a much larger radar reflectivity than a lot of small ones, even when the summed mass is the same in both cases. This means that the simulated radar and satellite signals are sensitive to the assumptions that are made in the microphysical scheme. Given that we have fully coverage of radar and geostationary satellites in Germany, we are in an ideal situation to examine many of the physical assumptions and parameters in the model.
In this presentation we will show how we have used radar and satellite information to prepare the RUC microphysics for operational forecasts. Our objective has been not only to improve the forecast scores, but also to get "more-physical" clouds, as seen by those remote systems. We have focused on radar reflectivities and on three different radiation channels from the Meteosat-SEVIRI instrument. Those channels provide information about cloud thickness, cloud height and particle size. We will show how the information from the radar and the different channels provides a complementary view, as often variation in microphysical assumptions can be directly detected by only one observation system.

**ID: 42, Poster**

## Towards Evaluating Microphysical Pathways Of Midlatitude Snow Formation in the ICON Model

1) Julian Meusel* (Karlsruhe Institute of Technology (KIT), Institute of Meteorology and Climate Research), 2) Corinna Hoose (Karlsruhe Institute of Technology (KIT), Institute of Meteorology and Climate Research), 3) Maximilian Maahn (Leipzig Institute for Meteorology (LIM), Leipzig University), 4) Nils Pfeifer (Leipzig Institute for Meteorology (LIM), Leipzig University)

In warm clouds, the microphysical pathways governing rain precipitation are well-established. However, the intricate interplay among ice crystals, liquid water, cloud dynamics and aerosol particles during snowfall formation remains poorly understood. This knowledge gap introduces uncertainties in modelling cloud microphysics. As current numerical models treat cloud and precipitating ice hydrometeors - such as small ice particles, snow, graupel and hail - with a limited number of prognostic variables, they do not capture the full complexity of the microphysical processes. This study leverages data from the Video In Situ Snowfall Sensor (VISSS), offering detailed insights into particle size, shape, and fall velocity, along with radiosounding data from the Intensive Observation Period (IOP) from February to mid March 2024 and local remote sensing data at Hyytiälä in Finland. This multi-faceted dataset aims to constrain and refine the microphysical representation of snow in default double-moment scheme of ICON (Seifert & Beheng, 2006) and the Predicted Particle Properties (P3) scheme (Milbrandt & Morrison).
The primary objective is to enhance our understanding of microphysical processes by quantifying how riming, aggregation and depositional growth processes are involved in snowfall formation in terms of frequency of occurrence and total snow mass. This will be accomplished through a comprehensive evaluation of snowfall microphysical pathways within the ICON model simulations. This study will utilize both the standard two-moment and P3 microphysical schemes, and will be compared against variables obtained through a machine learning retrieval process applied to the VISSS data collected during the IOP.
The poster presentation will showcase preliminary simulation results of snowfall events observed during the IOP. A particular focuss will be placed on process rates for snowfall formation, especially on secondary ice production (SIP) processes. Results from simulations using the default double-moment and the P3 microphysical scheme will be compared with VISSS, remote sensing and field campaign data located in Hyytiälä.

## Session 3.A: Prediction scales and model development. Modeling elements in nowcasting

**ID: 86, Oral Presentation**

## Application of a predictive recurrent neural network for quantitative precipitation nowcasting

1) Mst Mahfuja Akter* (Institute for Geosciences, Department of Meteorology, University of Bonn), 2) Silke Trömel (Institute for Geosciences, Department of Meteorology, University of Bonn)

Deep learning has recently become a very effective tool in radar meteorology for precipitation nowcasting. Predictive deep learning aims to learn time series and sequential data to predict future sequences, where the data is assumed to have modular structures. A predictive recurrent neural network (PredRNN) has been implemented with spatiotemporal long and short-term memory (ST-LSTM) units and additional connections between time steps and forces memory states to flow throughout the network. The model is further extended with a decoupling and reverse sampling mechanism to learn long and short-term dynamics to model the shape deformation and motion trajectories more efficiently. Polarimetric rainfall retrievals based on specific attenuation AH and specific differential phase KDP (R(AH, KDP)) are developed within the research unit RealPEP by using the Polara C++ platform from the German Weather Service (DWD). The generated rainfall maps with 5-minute temporal resolution covering the whole of Germany are fed into the PredRNN model. We investigated daily precipitation events and resized composite images for efficient data management. So far a total of 192 sequences (18 images per sequence) have been used to train, while 48 sequences are used to test the model. For the model evaluation, 6 sequential input images are used to predict the future 12 images. The PredRNN model is also opposed to an extended version of the spectral prognosis model (SPROG-LOC), which estimates spatially localized parameters of the inherent auto-regressive (AR) process. A primary comparison with SPROG-LOC showed that PredRNN outperforms. However, the experiment is still preliminary, and the best hyperparameter set has yet to be found. We will also train the model with the polarimetric radar variables to investigate further improvements. Furthermore, we aim to exploit the PredRNN to combine the predictive information content of radar measurements with satellite-based retrievals, e.g. MTG-FCI satellite-based cloud products and probability index fields for convective initiation, to further improve the lead time.

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**ID: 125, Oral Presentation**

## Enhancing radar-based nowcasting of heavy precipitation using IoT Rain Sensors and Machine Learning: A Field Study in Four German Cities

1) Annika Jahnke-Bornemann* (hydro & meteo GmbH), 2) Alrun Jasper-Tönnies (hydro & meteo GmbH), 3) Thomas Einfalt (hydro & meteo GmbH)

The "heavyRain" project (duration: 2022 – 2025) aims to improve short-term, radar-based forecasting of heavy rainfall events by integrating machine learning (ML) methods with Internet of Things (IoT) sensors. In a field trial conducted in four German cities—Bochum, Hagen, Lübeck, and Lüdenscheid—50 IoT-compatible low-cost rain sensors are deployed in each city. These sensors use an automotive infrared rain sensor, combined with a LoRaWAN transmitter and a photovoltaic element. LoRaWAN (Long Range Wide Area Network), a low-power wireless protocol, is already widely available in these cities. The sensors can distinguish between dry conditions and seven rainfall intensity levels, transmitting minute-averaged data through the municipal LoRaWAN network. This data is automatically collected, validated, and made accessible for further use. Despite being single-point measurements, the dense network of sensors offers the potential to better capture the spatial structure of rainfall events due to their rapid response, even to low rain intensities. With broad deployment and optimized placement, this network is expected to enhance rainfall pattern detection at scales of 0.5 to 1 km, complementing gauge, radar and satellite data.
The project aims to utilize these sensor data to improve radar-based nowcasting. ML methods will be integrated with a classical, cell-based nowcasting algorithm implemented in the SCOUT software (hydro & meteo), which interpolates motion vectors into a 2D vector field, accounting for cell rotation and divergence, using a semi-Lagrangian method for extrapolation of radar-measured rainfall fields. Nowcast ensembles are generated based on observed uncertainties in cell detection, offering reasonable accuracy in predicting cell direction and path. However, challenges remain in forecasting cell genesis, growth, and decay. This project examines whether ML-generated insights at the cell level can address these gaps. Furthermore, the integration of additional data sources, such as satellite and radar volumetric data, will be assessed for potential improvements to nowcasting accuracy.

### Acknowledgements

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**ID: 117, Poster**

## Localized Radar-Based Nowcasting of Convective Rainfall

1) Daniel Eduardo Villarreal-Jaime* (KU Leuven), 2) Patrick Willems (KU Leuven), 3) Lesley De Cruz (Royal Meteorological Institute of Belgium; Vrije Universiteit Brussel), 4) Ricardo Reinoso-Rondinel (Department of Civil Engineering, KU Leuven; Royal Meteorological Institute of Belgium)

Accurate short-range rainfall forecasts, known as nowcasts, are crucial for providing early warnings of extreme precipitation and flooding, especially in urban areas with high population density. Traditional nowcasting techniques, such as extrapolating radar echoes from constant altitude plan position indicator (CAPPI) or lowest-angle plan position indicator (PPI), often struggle to predict the development and dissipation of convective storms effectively. To address these limitations, methods like RadVIL, which uses mass balance equations of Vertically Integrated Liquid (VIL), and Spectral Prognosis (SPROG), which employs an autoregressive (AR) model, have been developed. Recent advancements include Autoregressive Nowcasting using VIL (ANVIL), which models the growth and decay of VIL using an autoregressive integrated (ARI) process, decomposing VIL into multiple spatial scales and applying a separate ARI model to each scale. Another advancement called SPROG-Localized (SPROG-LOC) extends the SPROG approach, which is the deterministic version of Short-Term Ensemble Prediction System (STEPS), by estimating spatially localized parameters of the AR process, improving the accuracy of rainfall forecasts. Building on these recent methods, we propose a novel approach that combines ANVIL and SPROG-LOC, termed SLANVIL (SPROG-Localized Autoregressive Nowcasting using VIL). This integrated method leverages the strengths of both techniques, aiming to improve nowcasting performance, particularly in scenarios with large, non-uniformly distributed precipitation areas and isolated convective features. While we are currently in the process of obtaining preliminary results and its probabilistic extension, we will present a first validation of our method for lead times up to 2 hours, comparing its forecast skill at various precipitation thresholds and spatial scales to established and operational nowcasting methods, such as pySTEPS-BE.

**ID: 124, Poster**

## Nowcasting model of thunderstorms intensity and probability TSP

1) Przemysław Baran* (Institute of Meteorology and Water Management Warsaw (IMGW-PIB)), 2) Anna Jurczyk (Institute of Meteorology and Water Management Warsaw (IMGW-PIB)), 3) Agnieszka Kurcz (Institute of Meteorology and Water Management Warsaw (IMGW-PIB)), 4) Krystian Specht (Institute of Meteorology and Water Management Warsaw (IMGW-PIB)), 5) Jan Szturc (Institute of Meteorology and Water Management Warsaw (IMGW-PIB))

The TSP (Thunderstorm Prediction) system enables the detection and forecasting of thunderstorms: probability and intensity, as well as tracking their movement in the assumed time horizon of 60 minutes. In addition, the model generates a quality field related to the availability and quality of the input data. Processed 1-minute reports from lightning detection system are used as an input data: density of intercloud lightning, density of cloud-to-ground lightning, maximum lightning jump, number of lightning jumps, within 10 minutes. The following data are also applied: radar data from the POLRAD network and from surrounding countries, such as VIL (Vertically Integrated Liquid), EHT (Echo Top Height), CMAX (Column Maximum), CAPPI (Constant Altitude Plan Position Indicator), and the $0^{o}$C isotherm altitude from the COSMO mesoscale model. Moreover, Meteosat satellite data processed with NWC-SAF software: CTTH (cloud top temperature and height) and RDT-CW (rapidly developing thunderstorm – convection warning) were used. The SVM (Support Vector Machines) machine learning model was applied to detect thunderstorms, using observations from synoptic stations located throughout Poland in a calibration process. Different decision tables were employed to predict the intensity and probability of thunderstorms. For forecast of the intensity class, the RDT-CW was taken into account (intensity class of current and forecast storm) with the intensity class obtained from the SVM model. For the probability forecasts, the RDT and CTTH data and parameters determined from the analysis of lightning dynamics were considered. The forecast of thunderstorm advection is based on movement vectors obtained from the nowcasting precipitation model SCENE. A dedicated system for graphical visualization of forecasts of the thunderstorm intensity and probability and the movement of thunderstorm cells was developed. The TSP model, running operationally at the Institute of Meteorology and Water Management in Poland, generates forecasts in spatial and temporal resolution of 1 km and 5 min, respectively, up to 60 min ahead with a time step of 10 min.

**ID: 78, Poster**

## Advanced Heavy Rain Forecasting: Artificial Intelligence-Driven Insights from High-Density Optical Rain Sensor Networks

1) Alexander Buddrick (NIVUS GmbH), 2) Nibesh Shrestha* (NIVUS GmbH), 3) Abdellah Lemouedda (NIVUS GmbH), 4) Benjamin Mewes (Okeanos Smart Data Solutions GmbH), 5) Henning Oppel (Okeanos Smart Data Solutions GmbH)

Extreme convective rainfall is increasingly recognized as a prominent consequence of climate change, leading to substantial pluvial flooding as urban drainage systems are overwhelmed. Despite advancement in weather radar and different climate models, cloudburst rain events are usually underestimated or undetected, heightening risks further (Lengfeld and Marra, 2024). In topographically complex and reactive watersheds, the limitations associated with conventional precipitation monitoring tend to exacerbate. These heavy-rain events, if not detected properly, pose severe threats, causing extensive damage to the settlements and industries without timely warning within a short period.
With a motive to bridge this gap, we present the exemplary development of a cutting-edge AI-supported early warning system and cell detection (now-casting) of heavy rainfall events. Leveraging IoT-based optical rain sensors, our system captures high-resolution rainfall intensity data from a dense swarm network of rainfall sensors deployed across the target regions (Buddrick et al., 2023). These data are used in real time to forecast rain trajectories through a physical optical-flow method. Furthermore, these data are used to train the AI capable of predicting heavy rain up to 60 minutes in advance. This critical lead time enables residents and emergency responders to prepare, significantly reducing the chaos phase and allowing timely preventive action. Additionally, strategically placed water-level sensors are also used to monitor the rivers and streams, and their response to these heavy rain events.
The innovative heavy rain forecasting system has been in operation in three pilot locations in Germany - Liederbach am Taunus, Olpe and OOWV Oldenburg. Point of Interests (POIs) within each pilot area serve as forecast targets, allowing flexible, localized protection of high-risk areas. The POIs are visualized in a frontend interface, providing reliable, timely alerts to the emergency services and municipal authorities based on a heavy rain index and guidelines. Multiple rain events have been successfully detected and forecasting up to 20 minutes in advances, showcasing commendable efficacy and prowess for real-world deployment in mitigating rainfall-induced hazards.

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# Session 3.B: Prediction scales and model development. Hectometer scale modeling for precipitation

**ID: 123, Oral Presentation**

## Studies of Convection-Permitting Ensemble Forecasting for ICON-D2 with a 1km Nest over the Alps

1) Zahra Parsakhoo* (Deutscher Wetterdienst), 2) Chiara Marsigli (Deutscher Wetterdienst), 3) Christoph Gebhardt (Deutscher Wetterdienst), 4) Axel Seifert (Deutscher Wetterdienst), 5) Jan Keller (Deutscher Wetterdienst)

Within the context of the "Global-to-Regional ICON digital twin" (GLORI) project, a convection-permitting ensemble forecasting is established in order to study the predictability of high-impact weather events with high-resolution modeling (up to 500 m) and the influence of the land-surface—atmosphere coupling mechanisms. At the DWD, ICON-D2-EPS is the limited-area high-resolution component of the ICON modeling system, running as an ensemble of 20 members at 2 km horizontal resolution over Germany and surrounding areas. The perturbed initial conditions are provided by the km-scale ensemble data assimilation system KENDA, run at the same resolution, assimilating a wide range of observations, including radar-derived radar volumes. Boundary conditions are provided by ICON-EPS, the global ensemble with a refinement at 13 km over Europe and is refreshed every 3 hours. In this work, we employ a nested domain with horizontal resolution of 1-km in the southern region of the ICON-D2, encompassing the Alps mountains. We run a 24-hour forecast simulation starting at 00UTC on the 21st of June 2022, with 20 ensemble members. The choice of the date is crucial as it corresponds to a day when the DWD recorded instances of heavy rain and hail in southern Germany. In our study, we perform all experiments using a two-moment microphysics scheme. Additionally, we incorporate the standard operational model perturbations and subsequently analyze the influence of various convection schemes on the predictability of processes that lead to convection development. Specifically, we examine the behavior of the convection scheme in two configurations: shallow convection only and deep convection parameterization in the so-called gray-zone-tuning version. By selectively enabling and disabling these schemes, our goal is to evaluate their individual contributions to predictability. Following this, we implement a tailored variant of the stochastically perturbed parameterization scheme (SPP) in ICON in order to delve into the influence of some uncertain parameters within either microphysics or turbulent parameterization, further advancing our understanding of its effects on the model performance.

# Session 4.A: Seamless prediction. Data assimilation integrating nowcasting and new observations

**ID: 23, Oral Presentation**

## Assimilation of Lightning and Reflectivity Texture Fraction in ICON-LAM

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Since mid-2024, the German Weather Service's Rapid Update Cycle (RUC) has been running operationally, marking the culmination of work that began in 2016, in response to catastrophic floods caused by extreme summer precipitation. The core of the RUC is the ICON-LAM regional model, running with 2-moment microphysics and a 1-hourly data assimilation cycle.
A key feature of the RUC's data assimilation process is the incorporation of not only conventional observations but also cloud- and precipitation-dependent data, such as radar reflectivities and radial winds, and visual and infrared wavelengths from the SEVIRI instrument. The implementation of 2-moment microphysics has notably improved the simulation of convection and precipitation, leading to a reduction in the rejection rate of precipitation-related observations during data assimilation and weaker a priori biases for the assimilation increments to overcome. These advancements have paved the way for the inclusion of additional precipitation-related observations, including lightning flash rate and convective object features derived from the cell-tracking system used in nowcasting.
Nevertheless, substantial challenges remain in constraining convective processes via hourly data assimilation, in particular because convective systems are nonlinear, non-Gaussian, and often discontinuous, making them difficult to constrain with typical assimilation methods. Here we investigate how the assimilation of convection-related quantities can be improved by considering the so-called texture fraction, a quantity that measures observation-model misfit on customizable scales and thresholds. We apply this principle to two convection-related observation types: two-dimensional radar reflectivity composites and lightning flash rates from ground-based antennas. We show that judiciously choosing the length scales and thresholds of this quantity can improve forecast precipitation within the first one to three forecast hours following an assimilation update.

**ID: 48, Oral Presentation**

## Assimilation of 3D polarimetric microphysical retrievals using the operational ICON model framework of DWD

1) Armin Blanke* (Institute for Geosciences, Department of Meteorology, University of Bonn), 2) Roland Potthast (Deutscher Wetterdienst), 3) Silke Trömel (Institute for Geosciences, Department of Meteorology, University of Bonn)

The use of dual-polarization radar data for model evaluation and data assimilation (DA) has the potential to enhance the representation of microphysical processes in numerical weather prediction (NWP) models and short-term quantitative precipitation forecasts (QPFs). Reimann et al. (2023) evaluated in a first study but for only two stratiform and one convective rainfall events in the summers of 2017 and 2021 the benefits of radar-derived liquid water content (LWC) and ice water content (IWC) in data assimilation. These two quantities are derived from observations of the operational dual-polarimetric C-band radar network of the German national meteorological service (DWD, Deutscher Wetterdienst) and assimilated into the operational convective-scale NWP model ICON-D2 of DWD using the ensemble-based KENDA (Kilometer-Scale Ensemble Data Assimilation system) framework. This study extends the work by Reimann et al. (2023). E.g. since spring 2021, the radial resolution of the radar volume scans has been increased from 1 km to 0.25 km, enabling also to increase the accuracy of the microphysical retrievals. We present our advanced setup, including e.g. $Z_{\mathrm{DR}}$ calibration, and will show our preliminary results on the performance of different assimilation configurations. The configurations are the assimilation of conventional observations (CONV), the additional assimilation of 3D reflectivities ($Z_{\mathrm{H}}$), the assimilation of 3D LWC or IWC below or above the melting layer instead of $Z_{\mathrm{H}}$ where possible and the joint assimilation of all radar sets together with CONV. We demonstrate how the use of updated retrievals using both the new higher radial resolution only and revised optimized DA settings compares to previous assimilation results from Reimann et al. (2023). Since the accuracy of state-of-the-art polarimetric microphysical retrievals is still reduced in the presence of riming, we focus on stratiform events only, such as the precipitation event on 14 July 2021 in the Ahr valley and the recent event on 31 May 2024 in Bavaria and Baden-Württemberg. Both events led to devastating floods. Further investigations are underway to apply the double-moment bulk microphysics scheme in the data assimilation framework, which is potentially more suited to digest the polarimetric information content compared to the single-moment scheme.

**Acknowledgements**

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**ID: 72, Oral Presentation**

## Commercial Microwave Link (CML) Data Assimilation with the LETKF

1) Klaus Vobig* (Deutscher Wetterdienst), 2) Christian Chwala (KIT (IMK-IFU)), 3) Julius Polz (KIT (IMK-IFU)), 4) Roland Potthast (Deutscher Wetterdienst), 5) Klaus Stephan (Deutscher Wetterdienst)

In this study, we examine the assimilation of a novel data source, namely commercial microwave link (CML) data. Originally, CMLs are employed for the interconnection of cell phone towers operated by mobile network providers, however, CML data also contain valuable information about atmospheric conditions at the ground level due to interactions of the transmitted radiation signal with, for example, raindrops. In fact, CML data are already successfully used for the purpose of quantitative precipitation estimation with high spatio-temporal resolutions and are becoming an important complement to radar data in this respect.
Here, we deal with the assimilation of CML attenuations in NWP models and investigate whether CML data are also able to improve precipitation forecasts and how the effects of a CML data assimilation compare to those of an assimilation of other observation types, such as radar data. An important building block of this work is the use of EMVORADO, originally a radar forward operator, to compute a simulated model equivalent for each CML observation. Furthermore, the state-of-the-art, convective-scale ICON-KENDA ensemble data assimilation framework—based on an implementation of the LETKF and the regional NWP model ICON-D2 covering central Europe—is employed for our numerical calculations.
Performing single-time assimilation experiments, we study internal details of the LETKF assimilation process, spatial distributions of increments for the temperature and specific humidity, and the behavior of the NWP model in short-time periods directly following an assimilation—and compare these results with those obtained from an assimilation of conventional or radar data. We are able to show that an assimilation of CML data, even on top of an assimilation of either conventional or a combination of conventional and radar data, is able to accurately initiate new convection and to significantly improve the fractional skill score by up to 10%.

**Acknowledgements**

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**ID: 121, Oral Presentation**

## Evaluate the Impact of Dual-Polarization Radar Data Assimilation Using Observation Operators

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The characteristics of simulated dual-polarimetric (dual-pol) parameters are significantly affected by configurations of dual-pol operators, leading to different covariance structures and results of data assimilation. In this study, the simulated reflectivity (ZH) and differential reflectivity (ZDR) are obtained via two different calculation methods, analytic and numerical integration of the scattering amplitude (SA). , The former fits the SA with power law to obtain an analytic solution while the latter integrates the SA bin by bin. The results show that the ZHH structure can be well simulated by the analytic integration method, but it leads to negative ZDR values for small raindrops and exaggeratedly large ZDR values for large raindrops. . Besides, the joint frequency between ZDR and ZHH is different from observation. On the contrary, the numerical integration method presents reasonable simulation of both ZHH and ZDR and well capture the joint frequency pattern of ZHH and ZDR. To sum up, directly integrating SAs bin by bin results in a reasonable ZDR structure in the background field and leads the analysis closer to the observation.

**ID: 127, Oral Presentation**

## Latest Result of Including ZDR Column for Enhanced Radar Data Assimilation at German weather Service (DWD)

1) Kobra Khosravian* (Deutscher Wetterdienst), 2) Jana Mendrok (Deutscher Wetterdienst), 3) Alberto de Lozar (Deutscher Wetterdienst), 4) Klaus Stephan (Deutscher Wetterdienst), 5) Ulrich Blahak (Deutscher Wetterdienst)

Radar data assimilation has been operationally used in the short-range ensemble numerical weather prediction (SRNWP) system (ICON-D2-KENDA LETKF system) at DWD since 2020 (radial wind from March 2020 and reflectivity from June 2020). It is in addition to the traditional Latent Heat Nudging (LHN) of 2D radar-derived precipitation rates.
Moreover, the study of radar data assimilation in numerical weather prediction (NWP) models, especially its impact on short-term forecasts, has gained significant focus recently at DWD. The seamless Integrated Forecasting System (SINFONY) project, which leads a short-term forecasting system for convective events from minutes up to 12 hours, clearly demonstrates the benefits of radar data assimilation in enhancing short-term forecast accuracy.
Furthermore, the integration of polarimetric radar parameters as a novel observational source into the data assimilation system at DWD has recently gained attention. Among these parameters, the ZDR column—defined by differential radar reflectivity (ZDR)—stands out as a distinct vertical layer of positive ZDR above the 0°C level. This feature is closely associated with deep convective storms and can indicate large raindrops or hail. We present our latest results on incorporating the ZDR column as a new observational input in Observing System Simulation Experiments (OSSE), complementing radial wind and reflectivity data within DWD's operational data assimilation framework.

### Acknowledgements

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**ID: 128, Oral Presentation**

### High resolution data assimilation in the GLORI Project

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The GLORI (Global-to-Regional ICON) project, born from the trilateral collaboration between German, Italian and Swiss institutions, aims to develop a global to regional digital twin based on the prediction capability of the ICON modeling system. One of the main focuses of the project is to improve forecasts, including quantitative precipitation forecasts, at different scales by exploiting the knowledge and capabilities known about high resolution.
The model integration domain encompasses the Italian peninsula and includes areas characterized by complex orography where high resolution is expected to better resolve physical processes and provide more accurate forecasts. The improvement is conditioned by several factors that are concurrently investigated by the different research groups involved in the project. The relevant topics for high resolution are the description of the physical processes, the improvement of the ensemble and the data assimilation.
In this context, this work presents the first step towards high-resolution assimilation by investigating the case study of the flood in Emilia-Romagna last October. The ultimate goal is the direct assimilation at 1 km, which requires a thorough assessment of the entire assimilation chain. Achieving this involves a new evaluation of the thinning and averaging of observations, their localization and the observation error. For this reason, the first step is to analyse and evaluate the behavior of assimilation at 2 km, with nesting at 1 km.
The system and tests results will then be described. Results include QPF verification over forecasts performed both using fractions skill score and dichotomous scores.

**ID: 98, Poster**

## Using a 3D Wind retrieval algorithm to improve the understanding of dynamics of hail cells in Germany

1) Tobias Scharbach* (Institute for Geosciences, Department of Meteorology, University of Bonn),
2) Silke Trömel (Institute for Geosciences, Department of Meteorology, University of Bonn)

Understanding the life cycle of thunderstorms and hail cells is crucial for improved nowcasting of severe weather and for improving NWP models. Dual polarimetric weather radars offer the simultaneously analyses of the microphysics and dynamics of severe weather events. This study deals with the combined analysis of the dynamics and microphysics of hail cells in Germany. Microphysical information is carried out by polarimetric information taken from the DWD (German Weather Service) C-Band radar network, to be able to investigate typical signatures associated with thunderstorms (e.g. the updraft region using the differential reflectivity), while the Doppler capability of the radars is utilized to get information about the dynamics of the systems by retrieving 3D wind fields using the open-source algorithm Pythonic Direct Data Assimilation (PyDDA). PyDDA uses the 3D variational (3DVAR) framework, in which the sum of various cost functions is minimized. These individual cost functions (parameters) are depending on the radar measurements (Doppler winds), atmospheric dynamical constraints (e.g. the continuity equation) and optionally also on other parameters, such as wind information from models, or observations of radio soundings. Various difficulties in the minimization process of the final cost function arise, as it is unclear to what extent the parameters should be weighted in order to reflect reality as accurately as possible. The different weightings of e.g. the continuity equation, or the Doppler information from the radars can cause unrealistic updraft velocities. A precise retrieved 3D wind field is particularly important as comparative analyses with hail trajectories will be performed in the future. An attempt is made to obtain the best possible set of values for the parameters by performing a sensitivity study. These refined PyDDA retrieved wind fields are then compared with actual measurements and simulated counterparts. Furthermore, PyDDA retrieved wind fields are compared with those of other retrieval methods (e.g. with a novel variational 3D wind retrieval method developed by our project partners from Australia). Generally, this research aims to identify the processes by which hail events evolve, by highlighting the relationship between the storm dynamics and the microphysics.

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**ID: 135, Poster**

## Optimal exploitation of polarimetry for precipitation-induced flood forecast

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Recent extreme rainfall and flooding events in northern Italy have demonstrated the deficiencies of numerical weather prediction (NWP) models in forecasting the intensity and location of heavy events in the complex terrain region. As one approach to improve the representation and forecasting of precipitation, this study exploits radar polarimetry in data assimilation. In a first step, hybrid state-of-the-art polarimetric retrievals will be used to enhance the accuracy of precipitation maps in Northern Italy with its complex terrain. While to date, rainfall rates used for Latent heat nudging (LHN) are estimated based on horizontal reflectivity (Zh) only, this study explores a combination of specific attenuation at horizontal polarization (Ah) and specific differential phase (KDP) along with profile corrections to derive rainfall rates for Arpae-SIMC, Arpae Piemonte radars and additional gap filler X-band radar in Turin. This methodology is advantageous due to the variable's insensitivity to systematic biases arising from e.g. miscalibration and attenuation. The accuracy of Zh and (Ah, KDP) based rainfall rates will be evaluated with rain gages. In the ensuing step, these potentially improved rainfall rates are used for LHN in addition to the assimilation of 3D reflectivities and radial winds and the impact will be assessed.

### Acknowledgements

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# Session 4.B: Seamless prediction. Blending and probabilistic techniques based on nowcasting and NWP ensembles

**ID: 118, Oral Presentation**

## Current status of SINFONY – The combination of nowcasting and numerical weather prediction for forecasting convective events at DWD

1) Ulrich Blahak* (Deutscher Wetterdienst), 2) SINFONY Team (Deutscher Wetterdienst)

DWD's new Seamless Integrated Forecasting system (SINFONY) is targeted to improve very-short-range forecasting of intense convective events from observation time up to 12 h ahead for Germany. Weather radar is at the heart of it. The goal is to produce seamless ensemble forecast products in observation space, i.e., radar reflectivity composites, precipitation fields and convective cell objects, as well as informations on the probability of hazards like heavy precipitation, hail, wind gusts and lightning. These products will hopefully serve as basis to improve DWD's meteorological warnings (forecasters, automated systems) as well as the warnings of the German flood forecasting authorities.
There are different optimal forecast methods for different forecast lead times, and the idea is to improve and combine them in an optimal way. Focusing on convective events and their related hazards up to several hours, we developed in the last seven years in an interdisciplinary team
1) radar Nowcasting ensembles for areal precipitation, reflectivity (STEPS-DWD) and convective cell objects including hail and life cycle information (KONRAD3D-EPS) with good forecast quality up to 1-2 hours,
2) a new regional NWP ICON-ensemble model (ICON-RUC-EPS) with assimilation of 3D radar volumes, cell objects, Meteosat VIS and IR channels and hourly new forecasts on the km-scale, whose quality exceeds Nowcasting after forecast hour 1-2,
3) and to get the best of both worlds for our customers, an optimal combinations ("blending") of Nowcasting and NWP ensemble forecasts in observation space, which constitute the seamless forecasts of the SINFONY. Gridded combined precipitation and reflectivity ensembles are targeted towards hydrologic warnings. Combined Nowcasting- and NWP cell object ensembles help evolve DWD's warning process for convective hazards towards flexible "warn-on-objects.
4) Common Nowcasting and NWP verification systems for precipitation, reflectivity and cell objects help to continuously improve the SINFONY components.
For 2), efficient forward operators for radar volumes (EMVORADO) and visible/infrared satellite data enable direct operational assimilation of these data in an LETKF framework. Advanced model physics (2-moment bulk microphysics with prognostic hail) contribute to an improved forecast of convective clouds, whose simulated life-cycle proofed to be surprisingly realistic.
For 3), the ICON-RUC-EPS forecasts output simulated reflectivity volume can ensembles of the German radar network every 5'. Radar composites and KONRAD3D cell objects and their tracks are generated by the exact same methods as in the Nowcasting. These are seamlessly combined with the STEPS-DWD- and KONRAD3D-EPS Nowcasts with encouraging quality - resting upon the improvements for Nowcasting (1) and NWP (2).
Meanwhile the system has matured and is in the process of operational installation. A number of its components have been run continuously during the last four convective seasons. This presentation will give a short overview on the system components and its performance during the last years.

**ID: 122, Oral Presentation**

## Project IMA: seamless predictions at the Royal Meteorological Institute of Belgium

1) Lesley De Cruz* (Royal Meteorological Institute of Belgium; Vrije Universiteit Brussel), 2) Michiel Van Ginderachter (Royal Meteorological Institute of Belgium), 3) Maarten Reyniers (Royal Meteorological Institute of Belgium), 4) Alex Deckmyn (Royal Meteorological Institute of Belgium), 5) Simon De Kock (Vrije Universiteit Brussel; Royal Meteorological Institute of Belgium), 6) Idir Dehmous (Royal Meteorological Institute of Belgium), 7) Wout Dewettinck (Royal Meteorological Institute of Belgium), 8) Felix Erdmann (Royal Meteorological Institute of Belgium), 9) Ruben Imhoff (Deltares), 10) Arthur Moraux (Royal Meteorological Institute of Belgium), 11) Ricardo Reinoso-Rondinel (Department of Civil Engineering, KU Leuven; Royal Meteorological Institute of Belgium), 12) Mats Veldhuizen (Koninklijk Nederlands Meteorologisch Instituut), 13) Joseph James Casey (Vrije Universiteit Brussel), 14) Loic Faleu Kemajou (Royal Meteorological Institute of Belgium), 15) Anshul Kumar (Royal Meteorological Institute of Belgium), 16) Viktor Van Nieuwenhuize (Royal Meteorological Institute of Belgium)

Seamless prediction systems are designed to deliver frequently updated forecasts that span various timescales by combining extrapolations of the most recent observations - such as weather radar data - with numerical weather prediction models. End users such as hydrological services, local authorities, smartphone users and the renewable energy sector, require increasingly early and accurate forecasts, especially for fields with a high spatiotemporal variability such as precipitation. Moreover, downstream impact models such as (urban) hydrological models have a strong nonlinear dependence on the meteorological input. So in addition to being fast and accurate, we also need calibrated ensembles of forecasts to conduct a proper error propagation to assess the impact uncertainty.
In response to these requirements, many national meteorological services have introduced seamless prediction systems, with notable examples including DWD's SINFONY, Met Office's IMPROVER, and Geosphere Austria's SAPHIR. In Belgium, Project IMA (after the Japanese word for "now" or "soon") represents the country's seamless prediction approach, utilising the RMI's observations network, the gauge-corrected quantitative precipitation estimate RADQPE, the pysteps-be probabilistic rainfall nowcasting system, the INCA-BE analysis and nowcasting system, and the ACCORD NWP model configurations ALARO and AROME. Unlike many other seamless systems, Project IMA features seamless ensemble precipitation nowcasts from 0 to 6 hours, aimed to improve predictions of flash floods and their uncertainty.
We present the advancements within Project IMA and especially the novelties in pysteps. We share a glimpse of deep learning-based blending methods to extend forecast horizons and improve calibration, sharpness, and general utility for hydrologists, crisis managers, and other stakeholders.
Project IMA aims to integrate research swiftly into operational processes. It encourages contributing to open-source software such as pysteps, promoting transparency, reproducibility, and international collaboration, and supporting the UN's initiative for "Early Warnings for All" by 2027.

**ID: 19, Oral Presentation**

## Seamless Combination of Object-Based Probabilistic Nowcasting and NWP Ensemble of Convective Cells From KONRAD3D

1) Lukas Josipovic* (Deutscher Wetterdienst), 2) Nora-Linn Strotjohann (Deutscher Wetterdienst), 3) Gregor Pante (Deutscher Wetterdienst), 4) Ulrich Blahak (Deutscher Wetterdienst)

Convective events have long been one of the most difficult phenomena to predict, making them a major focus of the SINFONY project at the DWD. Our new product is at the forefront of this effort, designed to revolutionize short-range forecasting (up to 14 hours) for convective storms by seamlessly integrating enhanced nowcasting and numerical weather prediction (NWP) into one powerful, cohesive forecast tool.
In this work, we aim to combine convective cells detected through probabilistic nowcasting with those from numerical weather prediction (NWP). The detection of these cells is performed using KONRAD3D, a state-of-the-art method developed at the DWD to identify and track convective cells based on radar reflectivity. This approach can also be applied to cells simulated by NWP, as the model forward operator, EMVORADO, generates simulated radar data with the same structure and temporal resolution as actual radar observations.
First, the simulated cells are spatially clustered using the DBSCAN method. After clustering, each observed cell is linked to the nearest cluster of simulated objects. The properties of the simulated cells are then compared to those of the observed radar cells using a score known as the total interest. Only cells that exceed a certain total interest threshold—indicating the greatest similarity to the observations—are selected for combination. Finally, the selected simulated cells are spatially adjusted so that their centroid matches the position of the nearest observed cell. Simulated cells detected within a specific time window around the observation but not matched to an observed cell are excluded from further consideration.
We also perform ensemble nowcasting of observed cells. In this process, the position, movement, and severity are subjected to stochastic noise. Additionally, a parabolic lifecycle of cell severity is assumed. As a result, each observed cell receives a seamless forecast of its development through ensemble nowcasting, as well as from assigned model cells. Moreover, thanks to the model input, our approach can account for the formation of new cells, which offers an advantage over pure nowcasting.
For forecasters, we provide compact information in the form of representative members and occurrence probabilities for cells based on their severity. Since last year, the product has been under evaluation not only by the DWD but also by the ESSL Testbed. We present an overview of our product, along with statistical verification and a prominent case study.

**ID: 44, Oral Presentation**

## Seamless Integrated Rainfall Forecasts using Nowcasting and NWP-Ensembles

1) Christian Berndt* (Deutscher Wetterdienst), 2) Markus Schultze (Deutscher Wetterdienst), 3) Martin Rempel (Independent Radar Scientist, formerly Deutscher Wetterdienst), 4) Ulrich Blahak (Deutscher Wetterdienst)

Reliable and accurate short-term rainfall forecasts are crucial for effective weather warnings, particularly during the convective season. At Deutscher Wetterdienst (DWD), rainfall warnings traditionally rely on either nowcasting or numerical weather prediction (NWP). Recent advancements within the SINFONY project (Seamless Integrated Forecasting System) aim to deliver seamless ensemble forecasts of short-term rainfall. In addition, flood forecasting is an important application and has gained more focus after extreme flooding events in recent years. Here, we will present a seamless combination technique that integrates radar nowcasts from DWD's STEPS implementation with NWP forecasts from the new rapid update cycle of the ICON-D2 model. Moreover, we will show a thorough verification for a period in May and June 2016 with lots of severe convection and heavy rainfall.

The proposed method INTENSE (Integration of NWP Ensembles and Extrapolation) employs a localized Bayesian approach inspired by an ensemble Kalman filter. It begins with a stochastic extrapolation of current radar observations with a 5-minute lead time using STEPS. This is followed by a localized analysis of extrapolation and NWP ensemble spread. Next, a correction is applied to the extrapolation forecast, shifting it towards the NWP forecast. The local degree of correction depends on the comparison ensemble spreads, i.e., the higher the extrapolation spread in comparison with NWP spread, the stronger the correction towards NWP for the current lead time. This process is repeated iteratively, with the corrected data as the input for the next lead time.

INTENSE delivers combined ensemble forecasts consisting of 21 members with a maximum lead time of 12 hours at a spatial resolution of 1 $km^2$ and a temporal resolution of 5 minutes. Moreover, we provide spatial analysis of ensemble spread, exceedance probability for certain thresholds, as well as percentiles. Real-time test operations are running with a preliminary version since June 2024 and the evaluation by DWD meteorologists is about to start.

This contribution offers an overview of the seamless combination approach and presents verification results demonstrating its advantages over pure NWP and nowcasting approaches. Fraction Skill Score as well as Critical Success Index show a clear improvement in comparison with pure STEPS nowcasting and pure NWP forecasts. For short lead times, INTENSE performs similar to STEPS and for longer lead times it preserves the forecast quality of the ICON-D2-RUC model. Furthermore, we will show an example of a recent convective event and discuss shortcomings as well as future improvements.

**ID: 85, Poster**

## Scale-Dependent Evaluation of Seamless Short-Term Forecasts of Convective Precipitation

1) Martin Rempel* (Independent Radar Scientist, formerly Deutscher Wetterdienst), 2) Markus Schultze (Deutscher Wetterdienst), 3) Ulrich Blahak (Deutscher Wetterdienst)

Short-term forecasts up to 12h ahead are essential for precise and consistent warnings that help to increase the lead time for decision makers in emergency services. These warnings are typically based on nowcasting techniques and numerical weather prediction (NWP). In order to condense information from both forecast systems and to provide an improved basis for warnings, an integrated short-term ensemble forecasting system on the convective scale was developed in the ongoing DWD project SINFONY (Seamless INtegrated FOrecastiNg sYstem).
One key component is the seamless combination technique INTENSE (Integration of NWP Ensembles and Extrapolations). It adapts the Bayesian approach according to Nerini et al., 2019 by utilizing the ensemble Kalman filter in a dimension-reduced space. INTENSE seamlessly combines DWD's implementation of STEPS with the new pre-operationals rapid update cycle of ICON-D2. It provides precipitation forecasts up to 12h ahead with a spatial and temporal resolution of 5min and $1 \times 1 km^2$, respectively.
In terms of domain-wide and time-averaged verification metrics, the forecasts generated by INTENSE ideally seamlessly combine nowcasting and NWP. However, the accurate and consistent forecasting of small-scale structures like convective cells is important in meteorological and hydrological warning management. This may be affected by inconsistencies in the transition period from nowcasting to NWP due to spatial mismatches between them. Further, the forecast skill with respect to the typical size of small river catchments may be low for these phenomena.
In this contribution, we will present the results of a scale-dependent evaluation of INTENSE using days with convective situations in summer 2023 to quantify the spatial scale on which it provides useful information. Further, geometric object properties of contiguous precipitation structures are assessed statistically to quantify inconsistencies within the transition period.

**ID: 87, Poster**

## Verification and further development of KONRAD3D-SINFONY

1) Nora Linn Strotjohann* (Deutscher Wetterdienst), 2) Lukas Josipovic (Deutscher Wetterdienst), 3) Ulrich Blahak (Deutscher Wetterdienst)

The KONRAD3D-SINFONY (K3DS) product aims to provide the most accurate prediction of convective events by combining radar observations with predictions from the ICON Rapid Update Cycle (ICON-RUC) model. To achieve this, we move model cells spatially and temporally and modify them to match observed cells better and we add nowcasting cells to the ensemble. For increasing lead times, the impact of the observation and nowcasting diminishes and after about two hours the prediction is purely model-based.
To optimize the performance of K3DS systematically, we set up a framework to recalculate and evaluate the 2024 convective season. This allows us to measure the performance of K3DS and test which changes improve the product. K3DS depends on many underlying systems such as the radar composites, the cell detection algorithm, nowcasting, the model, and simulated radar sweeps. As our tests reveal disprepancies between predicted and observed convective cells, we can provide hints how these underlying systems can be improved. Here, we present up to which lead times nowcasting is relevant and quantify the spatial resolution of the ICON RUC model. Finally, we show how we condense the results into a clear visualization that nevertheless provides sufficient details about individual cells for forecasters.

# Session 5.A: Precipitation and hydrological models. Extreme precipitation events

**ID: 62, Oral Presentation**

## Revealing the Structure of Precipitation Extremes: a spatio-temporal Wavelet Approach

1) Svenja Szemkus* (Institute for Geosciences, Department of Meteorology, University of Bonn), 2) Sebastian Buschow (Institute for Geosciences, Department of Meteorology, University of Bonn), 3) Petra Friederichs (Institute for Geosciences, Department of Meteorology, University of Bonn)

In the BMBF-funded ClimXtreme CoDEx project, we use advanced data compression techniques to analyze and characterize high-dimensional spatio-temporal weather extremes. By reducing the number of degrees of freedom, we improve the signal-to-noise ratio, facilitating a more precise assessment and detailed characterization of extreme weather events.
Here, we present a novel approach using wavelet decomposition to capture and analyze the complex spatio-temporal characteristics of precipitation extremes. Wavelet decomposition has proven to be highly effective in uncovering underlying frequency structures in time series data and is well-suited for analyzing two-dimensional patterns. Previous applications to spatial precipitation fields demonstrate their benefit for a better understanding and improved description of precipitation events. We extend these methods to capture both spatial and temporal characteristics, providing a comprehensive description of three-dimensional precipitation fields across space and time.
We show that this approach is effective in capturing the diverse spatio-temporal features of precipitation extremes, enabling a more targeted and nuanced description of processes driving extreme weather phenomena. Our applications include comparisons of various datasets for their their representation of extreme precipitation events, with a focus on high-resolution data such as radar observations and simulations on convective-permitting scales. We also analyze and describe recent precipitation extremes in Germany, including the May/June 2024 flooding in southern Germany and the Ahr flooding in 2021.

### Acknowledgements

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**ID: 67, Oral Presentation**

## Simulating intra-event return period co-occurrences in short-duration intense precipitation events

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Design storms mimicking extreme rainfall events are essential for planning drainage networks and managing flood risks, as they serve as input to estimate the resulting flood hydrograph. They are typically characterized by high return periods of intensity-duration relationships, which are estimated from historical records. However, current methods for estimating design storms, such as block-maxima, fail to account for observed return period co-occurrence over different durations within rainfall events and tend to oversimplify and overestimate the total rainfall amount. Focusing on short-duration intense precipitation events recorded in Zurich (Switzerland), we investigated the dependencies between critical precipitation intensities over several duration intervals, namely over the 10-, 30-, 60-, 180-, and 360-min intervals. Our analysis reveals strong dependencies, with maximum and average pairwise return period Kendall's $\tau$ rank correlation coefficients over two of these duration intervals of 0.69 and 0.39, respectively. We model these multivariate relationships with a vine copula, which is then used to simulate critical precipitation intensities over different duration intervals, thus respecting the observed dependencies within rainfall events. These intensities are used to constrain a micro-canonical cascade model that produces the corresponding precipitation hyetographs. With the new introduced approach, we find a reduction of 29% on average in total storm volume compared to a common block-maxima approach for events with a 10-year return period on the 60-min interval. Yet, we also find that 10% of these events show an increase in the 10-min interval precipitation intensity. The new method allows for the simulation of extreme precipitation events that reflect observed intra-event return period co-occurrence and the results suggest potential implications for hydrological applications demanding realistic design storms.

**ID: 47, Oral Presentation**

## Extreme rainfall over West Africa: Current state and projected impacts of climate change

1) Marlon Maranan* (Karlsruhe Institute of Technology), 2) Andreas Fink (Karlsruhe Institute of Technology)

West Africa is increasingly experiencing socio-economic distress caused by floods due to extreme precipitation events, the frequency of which is projected to increase in light of climate change. Working towards adaptation strategies generally require reliable and ideally long-term observational datasets in order to increase the knowledge about the spatiotemporal nature of extreme rainfall in the region. Thus, leveraging the capabilities of the high-resolution, satellite-based Global Precipitation Measurement (GPM) dataset Integrated Multi-satellite Retrievals for GPM (IMERG), this study evaluates the present-day as well as future statistics of daily precipitation extremes over West Africa by utilizing an extreme value analysis approach. Extreme precipitation values in IMERG for the period 2001-2022 are modelled with the generalized extreme value (GEV) distribution through yearly-based block maxima sampling of daily rainfall. A decrease of spatial uncertainty is further accomplished by using the Regional Frequency Analysis (RFA) based on the so-called "Index-flood method".
Results show that high return values, up to around 300 mm at a 50-year return period, are largely found over the coastal areas of West Africa, highlighting, among other things, the influence of the coastal shape on the formation of intense land-sea breeze convection, and orographic enhancement of rainfall along the Guinea Highlands. Thus, while extreme precipitation is prevalent along the highly urbanized coast, return values decrease with (a) distance from the coastline, and (b) towards the climatologically drier Sahelian region. Overall, the spatial pattern of return values for a given return period are strongly correlated with the pattern of mean daily rainfall, which suggests that the magnitude of mean daily rainfall is widely driven by precipitation extremes.
In a further step, the projection of future precipitation extremes is compiled using the statistically downscaled dataset of CMIP6 models "NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6)". By determining the difference in the GEV parameters between future scenarios and the historical runs, an adjustment of the IMERG-based GEV parameters is accomplished to mimic a potential future state of the rainfall distribution ("Delta method"). Here, the most extreme scenario SSP5-8.5 projected onto the long-term period 2081-2100 suggest an increase of the return value magnitude by over 100% in the populous coastal region of West Africa. Together with growing urbanization and the rise of sea levels, West Africa is facing dire socioeconomic stress without dedicated action plans against flood risk, especially in the densely populated Guinea Coast region.

**ID: 54, Oral Presentation**

## Comprehending Meteorological Drought in the Tons River Basin, India: A Spatio-Temporal Assessment of Variability and its impact on water resources

1) Samiul Sk* (Jawaharlal Nehru University, New Delhi), 2) S Sreekesh (Jawaharlal Nehru University, New Delhi)

Meteorological drought, a climatic phenomenon with long-term precipitation deficits, significantly affects water resources, agriculture, and ecosystems in a region with monsoon rainfall. Precipitation is becoming more variable over space and time, and hydroclimatic extremes are occurring in all types of climates, more in a warming climate. The Tons River basin (one of the Ganges' major sub-basins) frequently experiences drought, which has a negative impact on agriculture, water resources, health, and food security, leading to out-migration from the region. The basin frequently experiences meteorological drought, primarily occurring during the monsoon months with more regional variability. In the present study, an attempt has been made to analyze the seasonal precipitation variation and characteristics of the meteorological drought in the Tons River basin over space and time in the Tons River basin. The study made use of 0.25° x 0.25° Daily Gridded Rainfall Data obtained from the India Meteorological Department for the duration from 1991 to 2024. The coefficient of variation, standardized precipitation index (SPI), and the Mann-Kendall test have been calculated to understand the pattern. Furthermore, to assess the effect of meteorological drought on surface water resources, regression analysis has been used. Surface water bodies have been extracted from the Landsat Satellite images using a convolutional Neural Network. The current study demonstrates that the Tons River basin was characterized by a severe meteorological drought in 2007-2008, 2009-2010, 2010-2011, and 2015-2015, out of which 2007-2008, had a more severe meteorological drought. Furthermore, the basin experienced 19 years of meteorological drought over a 34-year span between 1991 and 2024, ranging from moderate to severe drought. The results also reveal that drought intensity varies over space in the river basin. The study also demonstrated that surface water resources are also being affected by the extremely low precipitation. This spatio-temporal analysis of the rainfall pattern and the meteorological drought provides significant insights for policymakers and other stakeholders to enhance resilience to drought in the Tons River basins.

**ID: 93, Oral Presentation**

## Prognostic ParFlow Integrated Hydrologic Model Applications at Stakeholder Scale Over Central Europe

1) Klaus Görgen* (Research Centre Juelich), 2) Alexandre Belleflamme (Institute of Bio- and Geosciences (IBG-3, Agrosphere), Forschungszentrum Jülich (FZJ), Jülich), 3) Suad Hammoudeh (Institute of Bio- and Geosciences (IBG-3, Agrosphere), Forschungszentrum Jülich (FZJ), Jülich), 4) Stefan Kollet (Institute of Bio- and Geosciences (IBG-3, Agrosphere), Forschungszentrum Jülich (FZJ), Jülich)

Integrated physics-based hydrologic models (IHMs) have evolved into versatile tools constituting a cornerstone of many water resources and hydrologic hazard impacts applications from catchments to global model domains. IHMs allow for a physically consistent terrestrial water cycle representation, where groundwater and surface processes interact. To simulate groundwater-to-atmosphere feedbacks more realistically and account for the lateral redistribution of water, IHMs are hence increasingly incorporated into coupled Earth system models. Here we show applications of high-resolution prognostic simulations with the IHM ParFlow (https://github.com/parflow). Since 2020, ParFlow, with its integrated Common Land Model, is applied on GPUs in an experimental quasi-operational setup over central Europe, at a spatial resolution of approximately 600m for daily 10-day forecasts in a 52 member probabilistic forecast ensemble driven by ECMWF forecasts. Additionally, a 7-month seasonal prediction ensemble is run each meteorological season. Informed primarily by agricultural stakeholder needs in a co-design process, we provide diagnostics, such as water table depth, seepage water, plant available water, total water storage, etc., of the current state and the near-term evolution of the terrestrial water cycle through specific, targeted interfaces to data and information products (e.g., https://wasser-monitor.de, in German). The seasonal predictions are disseminated with a focus on water availability through an experimental Water Resources Bulletin (https://www.adapter-projekt.de/bulletin/index_en.html) that shows subsurface monthly water storage anomalies, including shallow groundwater down to 60m depth, with reference to a long-term ParFlow climatology, that captures the recent hydrometeorological extremes very well. ParFlow prognostic capabilities have also been demonstrated through a process-based analysis of forecasts and hindcast runs of the 2021 extreme flood event in western Germany and eastern Belgium. While this is an uncalibrated model, ParFlow well simulates many aspects including magnitude and timing of this extreme event. The physical representation of groundwater-surface water interactions affords hypothesis testing and is used to improve our process understanding of the 2021 flood event.

**ID: 133, Oral Presentation**

## GSDR: A global sub-daily rainfall dataset for understanding extreme precipitation

1) Amy Green* (Newcastle University), 2) Matt Fry (UK Centre for Ecology and Hydrology), 3) Stephen Blenkinsop (Newcastle University), 4) Hayley Fowler (Newcastle University), 5) Elizabeth Lewis (School of Engineering, Manchester University), 6) Selma Guerreiro (School of Engineering, Newcastle University)

Precipitation extremes result in flooding and droughts, causing substantial damages and loss of life. Understanding the variability of precipitation extremes with climate change is challenging, as we do not fully understand processes causing extreme precipitation under current climate variability. The INTENSE project focuses on understanding of the nature and drivers of global sub-daily precipitation extremes and change on societally relevant timescales. As part of this, a global sub-daily precipitation dataset (GSDR) has been collected, containing hourly rainfall data from a wide range of sources (25,000 rain gauges across over 200 territories). The dataset is quality controlled (rule-based open-source methodology, GSDR-QC), combining a number of checks (e.g. neighbouring gauges, known biases and errors, Expert Team on Climate Change Detection and Indices thresholds).
Recent updates to the dataset have been made – including data from 2018-2023 – essential for understanding the current and future impacts of climate change, with current work is focused on the development of a regularly (semi-automated) global dataset, providing an extra decade of GSDR data, particularly relevant for understanding the behaviour of precipitation extremes in a changing climate, at a global scale. A set of global hydroclimatic indices have been produced (GSDRI), characterising key aspects of shorter duration precipitation variability, including intensity, duration and frequency properties, which are publicly available where possible alongside a precipitation climate indices dataset.

**ID: 129, Oral Presentation**

## Hybrid modelling setups for real-time urban pluvial flood mapping

1) Daan Buekenhout* (KU Leuven), 2) Patrick Willems (KU Leuven), 3) Ricardo Reinoso-Rondinel (Department of Civil Engineering, KU Leuven; Royal Meteorological Institute of Belgium)

Extreme rainfall events and the resulting pluvial floods are projected to increase in frequency due to climate change. Accurate and timely flood forecasts are crucial for mitigating the impact of these events, but traditional hydrodynamic models are computationally expensive, limiting their use for real-time processing of probabilistic rainfall forecasts. This study explores the development and evaluation of spatiotemporal surrogate models that can rapidly convert rainfall nowcasts into probabilistic flood maps for highly urbanized catchments. The focus of this research is on the hybrid surrogate modeling approach, which combines a simplified, physically-based hydrodynamic model with a data-driven component. The study investigates different formulations of the simplified physically-based model setup, ranging from coarse-resolution 1D-2D coupling to models that entirely neglect the subsurface sewer system dynamics. These simplified models are then paired with a data-driven module that bridges the gap to the detailed flood inundation patterns simulated by the reference hydrodynamic model. This hybrid structure offers a potentially beneficial balance between physical representation and computational efficiency. In an initial analysis for the city of Antwerp, Belgium, the hybrid modelling approach resulted in a calculation speed improvement with a factor between 30 and 300, depending on the selected physically-based model component. Interestingly, utilisation of a relatively fast physically-based model which ignores the sub-surface component altogether, resulted in the best $R^2$ at the peak of the flood event (0.86), slightly better than a 1D2D physically-based model component with thrice the calculation time with ($R^2 = 0.85$). These preliminary findings will be further investigated through an extended analysis incorporating a wider range of storm events and additional physically-based model configurations to better understand the trade-offs between model complexity, computational efficiency, and prediction accuracy.

**ID: 130, Oral Presentation**

## Evaluating the performance of X-band radars for QPE during heavy rain events in western Germany

1) Daniel Sanchez-Rivas* (Institute for Geosciences, Department of Meteorology, University of Bonn), 2) Silke Trömel (Institute for Geosciences, Department of Meteorology, University of Bonn), 3) Alexander Ryzhkov (NSSL, Norman)

Dual-polarisation X-band radars have become popular tools in the operational and research sectors to address a broad range of scientific goals: examining cloud microphysics, monitoring up-close and rapidly developing storms, quantitative precipitation estimation (QPE), among others. These weather radars can fill gaps in existing operational radar networks or provide precipitation estimates with higher temporal and spatial resolution in areas of particular interest, e.g., urban environments. This study thoroughly investigates rain-rate retrievals derived from polarimetric X-band measurements. In particular, events related to severe heavy rain that occurred in the Rhenish mining region (western Germany) are examined. The DWD operational C-band radar network is used to evaluate the performance of the X-band radars for QPE, but also to assess the improvements when using the latter as gap fillers. The advantages and main challenges of using X-band radars for QPE are also presented. For instance:
1. Attenuation resulting from rain is significant at shorter wavelengths. It was observed that at the X-band wavelength, the specific attenuation ($A_H$) and specific differential attenuation ($A_{DP}$) are up to three times larger than those at C-bands. Even more, heavy attenuation can lead to the total extinction of the signal in the presence of thunderstorms. 2. It is required to implement robust techniques for quality control, calibration monitoring, rainfall estimation and compositing of precipitation products based on polarimetric data collected by C-and X-band radars to generate reliable QPE products. 3. There are clear benefits of using rain estimators based on $A_H$ or the specific differential phase ($K_{DP}$) over traditional $R(Z_H)$ or $R(Z_H, Z_{DR})$ estimators as the former show a better performance in the presence of heavy rain when compared with rain gauge measurements, due to the independence of $A_H$ and $K_{DP}$ on radar power calibrations, less sensitivity to DSD variations, and being relatively immune to attenuation and beam blockage. However, methodologies especially devised to improve $R(Z_H)$ and hybrid $R(Z_H, A_H)$, $R(Z_H, K_{DP})$ estimators and overcome the issues related to power-based measurements are presented.

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**ID: 18, Oral Presentation**

### Precipitation forecast enhancements in Destination Earth: advancing toward km-scale Global simulations

1) Estíbaliz Gascón* (European Centre for Medium-Range Weather Forecasts (ECMWF)), 2) Benoît Vannière (European Centre for Medium-Range Weather Forecasts (ECMWF)), 3) Jasper Denissen (European Centre for Medium-Range Weather Forecasts (ECMWF)), 4) Maliko Tanguy (European Centre for Medium-Range Weather Forecasts (ECMWF)), 5) Ervin Zsoter (European Centre for Medium-Range Weather Forecasts (ECMWF)), 6) Irina Sandu (European Centre for Medium-Range Weather Forecasts (ECMWF))

The European Commission's Destination Earth initiative is developing several digital replicas (digital twins) of the Earth system, combining state-of-the-art Earth system models and observations. One such digital twin focuses on weather-induced extremes and has two main components: daily global high-resolution forecasts developed by ECMWF, and on-demand regional simulations developed by a consortium led by Météo-France.
The Global Extremes Digital Twin (Global DT) is designed to forecast extreme weather events worldwide with unprecedented precision, offering continuous, kilometre-scale global high-resolution forecasts. Currently, the Global DT uses ECMWF's Integrated Forecasting System (IFS) cycle 48r1 with a grid spacing of approximately 4.4 km (TCo2559).
This presentation highlights the significant improvements of global km-scale simulations performance for precipitation, especially in complex orographic regions, compared to the current operational IFS 9 km resolution forecasts. The Global DT reduces both the overestimation of small 24-hour precipitation values and the underestimation of extreme precipitation amounts observed in the 9 km forecasts, resulting in a smaller absolute bias. However, challenges in simulating convective precipitation remain, such as the failure to propagate marine convective systems further inland, to simulate localised convective events in flat areas and squall lines with realistic structures in tropical areas. Adjusting the cloud base convective mass flux within the convective parameterization shows potential in addressing some of these issues. However, further investigation is required before these changes can be applied operationally, as they may lead to a decrease in forecast skill in certain regions. Additionally, several case studies of extreme precipitation events have been explored at even higher resolutions to assess their potential for improving the detection of extreme weather.
Finally, we evaluated the benefit of km-scale information for flood forecasting with simulations using the river routing model CaMa-Flood, which is directly integrated in the Global DT workflow.

**ID: 88, Oral Presentation**

## The Southern German flooding in May and June 2024

1) Sebastian Buschow* (Institute for Geosciences, Department of Meteorology, University of Bonn), 2) Petra Friederichs (Institute for Geosciences, Department of Meteorology, University of Bonn), 3) Svenja Szemkus (Institute for Geosciences, Department of Meteorology, University of Bonn)

Between Mai 30th and June 6th 2024, heavy rainfall in Southern Germany lead to severe flooding in the Danube, Neckar and Main catchment. Hazardous events of this nature receive considerable public attention, particularly due to the ongoing debate around the impacts of man-made climate change. The BMBF funded research project ClimXtreme aims to improve our understanding of such weather extremes in a changing climate through physics, statistics and impact modeling. A main goal is the creation of a knowledge base and the dissemination of relevant information to decision makers as well as the interested public. As part of this initiative, ongoing state-of-the-art research is applied to current events and the results are published in the form of scientific reports. The analysis reveals that the southern German floods resulted from a mix of precipitation processes on several spatio-temporal scales including convection as well as large-scale stratiform rain. Compared to previous floods, the most remarkable characteristic is the large extent in space and time. The aggregated intensity, on the other hand, was not particularly unusual and has been slightly increased by the warming climate. Nevertheless, the reaction of river runoff was extreme, particularly on the scale of small river catchments: while the overall regional runoff was the second largest in the past century, several local runoff values had estimated return times well over 100 years.

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**ID: 34, Oral Presentation**

## Return Period Analysis of Maximum Daily Rainfall Disasters in the Zagros Mountains, Iran: March (2019)

1) Elham Mobarak Hassan (Department of Environment, Islamic Azad University, Ahvaz) 2) Ebrahim Fattahi (Department of Hydrometeorology, Research Institute of Meteorology and Atmospheric Science, Tehran), 3) Jeff (Jafar) Sepehri* (Earth and Space Science Dept., York University)

This study investigates the return period of heavy rainfall events in the Zagros Mountains of Iran, with a particular focus on the floods that occurred in March 2019. The annual and monthly variation and statistical characteristic of maximum daily rainfall variation were examined over the available data in the Karkheh River Basin, located in western Iran's Zagros Mountain. The return period of the extreme rainfall intensity is estimated using "HyfranPlus" to assess various probability distributions, including Generalized Extreme Value (GEV), log-normal, log-normal Type III, Pearson Type III, Gumbel, and Inverse Gamma. The result shows in the annual total rainfall did not exhibit a significant trend; however, maximum daily rainfall demonstrated an increasing trend, indicating a rise in heavy rainfall events. While the Gumbel distribution proved most effective for the 72-year record at Khorramabad, the Inverse Gamma distribution provided the best fit for shorter data periods, estimating return periods of 50 to 300 years for extreme rainfall events at different stations. However, at the Pol-Dokhtar and Nurabad stations, which recorded maximum daily rainfall of 139 mm and 101 mm, respectively, in March 2019, the statistical distributions indicated return periods ranging from 70 to 300 years. Notably, the highest daily rainfall over the long term did not occur in March or April. In March 2019, maximum daily rainfall exceeded the long-term average, a consequence of increased rainfall upstream that led to flooding downstream in the Karkheh basin. While the heavy rainfall events in March and April 2019—potentially linked to climate change—resulted in significant flooding and damage, other factors, such as alterations in land surface structure, particularly along riverbanks, also contributed to the increased human and financial losses. Overall, our research contributes to the understanding of hydrological extremes and informs strategies to mitigate flood-related damages in the Zagros Mountains, ultimately supporting climate resilience efforts in vulnerable regions.

**ID: 35, Oral Presentation**

## A globally-applicable conceptual model for extreme precipitation events

1) Paul Davies (Met Office), 2) David Flack* (Met Office), 3) Hayley Fowler (Newcastle University, Tyndall Centre for Climate Change Research)

Forecasting extreme precipitation events often comes with limited warning due to large uncertainties associated with convective precipitation. Given the vast socio-economic impacts of the resulting hazards of extreme rainfall, e.g., flash flooding and landslides, fundamental research into what causes these extremes remains an important priority for the community.
Using observational data from the UK a new four-stage conceptual model for extreme precipitation was developed. The conceptual model consists of i) a pre-conditioning phase, ii) a lifting phase, iii) the realization phase, and iv) the transition phase. Throughout the model a three-layered structure for the atmosphere exists: a conditionally unstable layer sandwiched between a low-level layer of increased stability and an upper-level stable layer. The conditionally unstable layer takes the form of a Moist Absolutely Unstable Layer (MAUL), and it is the release of the instability within the MAUL that drives the extreme rainfall.
To release the instability from the MAUL certain properties were observed. The MAUL needs to be associated with weak CAPE (typically $<$ 500 J kg-1 for the UK). The MAUL also requires a warm top to ensure that warm rain processes can dominate and increase the precipitation. However, to make the most extreme events the MAUL also needs to be deep whilst remaining within the other constraints.
The conceptual model was tested over Jakarta and shown to apply in the tropics. Thus, it is a globally-applicable model. Examination of extreme rainfall events in 2024 has shown the importance of the saturation fraction in distinguishing between extremes from convective activity (localised saturation fractions close to one) and large-scale activity (widespread saturation fractions close to one). The ability to distinguish between precipitation modes enhances the forecast via inference of the predictability and characteristics of the system likely to produce the extreme event.
Global model representation shows biases in MAUL base and CAPE suggesting that improved representation of extremes will require improved vertical profiles in the model. However, due to the sparse nature of observed profiles the constraints for the model are limited.
The novel conceptual model for predicting extreme precipitation could help increase the lead time for warnings of extreme events and help focus the planning of emergency responders and public to enable to increase awareness, preparedness, and ultimately save lives.

**ID: 84, Poster**

### Urban influences on convective rainfall across different city structures

1) Herminia Torelló-Sentelles* (Institute of Earth Surface Dynamics, University of Lausanne), 2) Gabriele Villarini (Department of Civil and Environmental Engineering, Princeton University), 3) Marika Koukoula (Institute of Earth Surface Dynamics, University of Lausanne), 4) Nadav Peleg (Institute of Earth Surface Dynamics, University of Lausanne)

Heavy short-duration convective rainfall, which is typically linked to flash floods, has been shown to be affected and generally intensified by urban areas. However, predicting the urban rainfall effect across different cities characterized by different structures (e.g., areas, density, and building heights) remains a difficult task since diverse effects have been reported across studies and the underlying dynamic and thermodynamic mechanisms remain unclear. Using the Weather Research and Forecasting (WRF) model, we simulate 11 convective storms that cross the city of Indianapolis, Indiana. We then replace the urban area of Indianapolis with those of eight other cities to assess how different urban structures affect rainfall. Rainfall intensity changes over the urban areas, when compared to simulations that exclude the cities, tend to be related to the size and structure of the city, namely, the proportion of buildings with an open arrangement. We find that half of the simulated storms intensify over and downwind of the urban centers. This intensification occurs when background wind speeds are low and the urban heat island effect is strong, resulting in increased vertical uplift and a deeper boundary layer, enhancing convection. The remaining half of the storms become suppressed over the cities, when background wind speeds are high, and the urban heat island effect is weak. In such cases, vertical motion strength and boundary layer height decrease, inhibiting convection due to reduced boundary layer moisture and strong deceleration effects at the surface due to increased urban surface roughness. Considering that urban population and city size is projected to increase in the coming decades, our results suggest that heavy rainfall may be further intensified over cities.

**ID: 95, Poster**

### Real-time assessment of rainfall extremity using observations and seamless short-term forecasts in small river catchments in Germany

1) Jan Bondy* (Deutscher Wetterdienst), 2) Christian Berndt (Deutscher Wetterdienst), 3) Ulrich Blahak (Deutscher Wetterdienst), 4) Vanessa Fundel (Deutscher Wetterdienst)

Small-scale, convective heavy rainfall events pose significant challenges for flood forecasting, particularly in smaller catchments where rapid response times, a lack of stream gauges and the different focus on larger scales of operationally used hydrological models complicate predictions. Therefore, we explore supplemental strategies to support German flood forecasting centers in order to enable an efficient assessment of the current meteorological situation and short-term predictions. The AREA product (Areal Rainfall Extremity Assessment) aims at complementing the flood forecasters' workflow based on hydrological modeling, by rapidly identifying catchments affected by intense rainfall. We provide a novel post-processing product containing areal rainfall in catchments augmented with information about its statistical extremity, highlighting flood risks based on purely rainfall-derived signals.
We derived all river catchments in Germany with areas ranging from 10 to 500 $km^2$. On that basis, areal rainfall using rain gauge-adjusted radar observations and seamless rainfall forecasts from the SINFONY product "INTENSE", with lead times of up to 12h, are computed. INTENSE combines radar-based nowcasting and NWP forecasts, updated every 5 minutes, which can be crucial in highly dynamic atmospheric conditions. To assess the extremity of a catchment rainfall event in real-time, we calculate return periods through extreme value analyses for multiple rainfall durations. The underlying extreme value distributions for the catchments are based on a 23-year dataset of radar climatology, combined with existing, regionalized long-term rain gauge statistics (DWD-KOSTRA), in order to extend the short radar time series and coarsely estimate longer return periods.
Whilst already running as a test system with observations, the integration of probabilistic forecasts, their combination with presently observed rainfall and the condensation of information is currently in progress. Furthermore, we also explore the possibility of incorporating antecedent precipitation or a national soil moisture product to refine the meteorological flood risk signal. In this poster presentation, we provide an overview of the AREA product and ongoing developments.

**ID: 96, Poster**

## Tailoring Weather Warnings in the DWD Warning Portal to Meet the Requirements of Flood Forecasting Centers

1) Maja Rüth* (Deutscher Wetterdienst), 2) Jan Bondy (Deutscher Wetterdienst), 3) Kira Riedl (Deutscher Wetterdienst), 4) Christian Vogel (Deutscher Wetterdienst), 5) Björn Reetz (Deutscher Wetterdienst), 6) Reik Schaab (Deutscher Wetterdienst), 7) Linda Noël (Deutscher Wetterdienst), 8) Heiko Niebuhr (Deutscher Wetterdienst), 9) Kathrin Feige (Deutscher Wetterdienst), 10) Vanessa Fundel (Deutscher Wetterdienst)

The RainBoW program ("Risk-based, Application-oriented and INdividualizaBle Provision of Optimized Warning Information") by the German Meteorological Service (Deutscher Wetterdienst/DWD) aims at renewing the weather warning system with a strong focus on the end users' needs. One of the main goals is to provide individualizable weather warnings for specialized application areas, since relevant warning thresholds with respect to meteorological criteria and forecast probability may vary significantly based on the unique use case. This also enables users from the hydrological sector to receive weather warnings tailored to their specific requirements. In order to support this individualized approach, we are developing the so-called warning portal—a toolbox for end-users to configure, receive, and visualize tailored warnings. The portal currently allows users to select weather elements and a corresponding pre-configured set of thresholds. These parameters are passed to the underlying web API and then used to compute occurrence probabilities for each threshold in custom areas of interest (e.g., specific places or uploaded geometries). In the future, users will be able to configure warning thresholds themselves and receive a notification if they are exceeded within their area of interest. A customizable visualization dashboard will complement the individualization. Furthermore, the web API will enable users to include individual warning information in their own automated processes by directly analyzing individual requests and returning the results in JSON format.

During the development process, we are exploring specific features aimed at hydrological users, including warnings that are based on specific aggregation metrics over individually relevant areas (such as river catchments). For instance, rainfall warnings can be based on spatial averages over catchments, presenting a purely rainfall-based signal for flood risks. In combination, we intend to provide return periods of rainfall events in catchments in order to directly assess and communicate their statistical extremity in the warning.

This contribution will provide an overview of current development topics of the warning portal prototype, with an emphasis on the features for flood forecasting centers. We also invite feedback from hydrological experts to better understand and integrate their specific requirements into our continuously evolving platform.

**ID: 102, Poster**

## Precipitation and hydrological events in Northwest Bulgaria since 2001

1) Hristo Popov* (Sofia University), 2) Tsvetelina Dimitrova (Hail Supresion Agency)

This study investigates the relationship between precipitation dynamics and hydrological responses in Northwest Bulgaria during the warm half of the year, a period critical for agricultural productivity and water resource management. With climate change intensifying variability in precipitation patterns, understanding these dynamics is essential for effective planning and mitigation strategies. The research employs the Soil and Water Assessment Tool (SWAT) and HEC-HMS hydrological models to assess the impact of seasonal precipitation on river basin hydrology. Data were collected from multiple rain gauges, encompassing a 24-year period from 2001 to 2024. This dataset facilitated an analysis of trends in rainfall distribution, intensity, and frequency, specifically focusing on their implications for surface runoff and groundwater recharge during the warm months. The models were rigorously calibrated and validated against historical discharge records from key rivers in the region, ensuring accurate simulation of hydrological processes. Preliminary results indicate a pronounced correlation between increased precipitation intensity and heightened runoff, leading to potential flooding risks, while extended dry periods exacerbate water scarcity for irrigation. Furthermore, the research highlights the significance of short-duration, high-intensity rainfall events, which disproportionately affect hydrological responses. The findings underscore the necessity for adaptive water management practices that account for the projected changes in precipitation patterns. By integrating detailed precipitation analyses with advanced hydrological modelling, this study provides valuable insights for policymakers and stakeholders in agriculture and water resource management. The outcomes aim to inform strategies that enhance resilience to climatic variability, ultimately contributing to sustainable development in Northwest Bulgaria.

**ID: 136, Poster**

## Automatic Early warning for severe thunderstorms in Piemonte, Italy

1) Roberto Cremonini* (Arpa Piemonte), 2) Renzo Bechini (Arpa Piemonte), 3) Valentina Campana (Arpa Piemonte), 4) Gabriele Fasano (Arpa Piemonte)

During the warm season, severe storms are one of the most significant threats to highly urbanized areas: strong winds, hailstorms, and high precipitation rates cause economic losses and even causalities. Driven by climate changes, the recent floods in Germany in May and Spain in November are clear examples of high-impact severe weather urbanized areas. UNFCCC stated that Early Warning Systems are effective tools for helping people adapt to climate change; such systems increase the chances of saving lives and livelihoods in the case of extreme weather events such as storms and floods. For several years, the Regional Agency of Environmental Protection (Arpa Piemonte), as part of the National Civil Protection, has operated a regional early warning system for severe storms based on weather radar observations. This study summarizes the achieved results and illustrates algorithm calibration outcomes and recent developments.

# Session 5.B: Precipitation and hydrological models. Evaluation, verification and interfaces

**ID: 60, Oral Presentation**

## Operational Hydrologic Ensemble Forecasts in Small Catchments – Implementing New Products for Precipitation Estimation and Seamless Predictions

1) Jens Grundmann* (TU Dresden, Institute of Hydrology and Meteorology), 2) Michael Wagner (TU Dresden, Institute of Hydrology and Meteorology)

Flood forecasting and warning for small catchments are challenging due to the short response time of the catchments on heavy rainfall events. Thus, disaster managers are interested in extended lead times to initiate flood defense measures, which can be obtained by employing forecasts of numerical weather models as driving data for hydrological models. To portray the inherent uncertainty of weather model output, ensemble hydro-meteorological forecasts can be used. Within the scope of the project HoWa-PRO (funded by the Federal Ministry of Education and Research, Germany) we develop a hydrologic ensemble forecasting system for flood early warning in small catchments with lead times up to 48 hours. The so-called sentinel watches meteorological ensemble forecasts of the German Weather Service (DWD). If a specific precipitation criterion is surpassed, the sentinel starts collecting and concatenating various established precipitation products for precipitation estimation based on radar (Radolan-RW), nowcast (Radolan-RV), and ensemble forecast (Icon-D2-EPS, Icon-EU) to initiate a hydrologic ensemble flood forecast. The results can be followed via the web platform howapro.de. Besides this renowned precipitation products, we set up a second hydrologic ensemble forecasting system using prototypic data of upcoming products for precipitation estimation and forecasting to explore their capabilities. Here we combine (1) observed radar data assimilated to precipitation gauges and commercial microwave links (pyRADMAN), and (2) the seamless prediction data SINFONY-INTENSE. The latter is a combination of nowcasting and numerical forecast ensembles. Both data products are delivered some minutes earlier than the established products which offer benefits for disaster managers. The sentinel system scales well with additional catchments which can be simulated in parallel. Currently, the sentinels for both data versions (established and upcoming precipitation products) are invoked each 30 min, shortly after new observed data is delivered. The used WeatherDataHarmonizer library (Wagner and Grundmann, 2023) ensures a temporally, spatially, and formally homogeneous precipitation data set with a lead time of maximum 180 h, a time resolution of 15 min, and a spatial resolution of about 1 km. Each component of the sentinel is robust in a sense of handling missing operational data or machine faults. Additionally to the technical aspects, we present results of operational hydrologic ensemble forecasts for selected events and catchments in Saxony, Germany, and compare the performance of both systems.

**ID: 49, Oral Presentation**

## Evaluation of precipitation products' characteristics over Germany for hydrologic model forecasts

1) Suad Hammoudeh* (Institute of Bio- and Geosciences (IBG-3, Agrosphere), Forschungszentrum Jülich (FZJ), Jülich), 2) Klaus Görgen (Institute of Bio- and Geosciences, Agrosphere, Forschungszentrum Jülich (FZJ), Jülich), 3) Alexandre Belleflamme (Institute of Bio- and Geosciences (IBG-3, Agrosphere), Forschungszentrum Jülich (FZJ), Jülich), 4) Julián Alberto Giles (Department of Meteorology, Institute of Geosciences, University of Bonn), 5) Silke Trömel (Institute for Geosciences, Department of Meteorology, University of Bonn), 6) Stefan Kollet (Institute of Bio- and Geosciences, Agrosphere, Forschungszentrum Jülich (FZJ), Jülich)

Precipitation is central to the Earth's hydrological cycle. Climate change is expected to increase the frequency and intensity of hydrometeorological extremes, highlighting the demand to improve hydrological forecasting to enable effective water resource management. Accurate precipitation data, as the main input for hydrological modeling, is key to enhance the forecast accuracy. This study evaluates the ECMWF High Resolution (HRES) NWP precipitation data jointly with other precipitation products of various origins (in-situ observations, meteorological radars, satellite observations, reanalyses). This assessment is performed in the context of our daily in-house integrated, high-resolution hydrological forecasts over central Europe, employing ParFlow/CLM driven by HRES. The European Climate Assessment & Dataset (ECA&D) in-situ daily precipitation observations serve as the reference for the 2014 to 2022 time span. The datasets evaluated include the ERA5 and COSMO reanalyses, HYRAS raster data, near real-time RADOLAN and climatological RADKLIM radar data, the OPERA radar composite with its EURADCLIM climatological dataset, and the two integrated multi-satellite products IMERG-Late and IMERG-Final. Results show that both HRES and ERA5 are well suited as atmospheric forcing for the ParFlow/CLM hydrological model runs, but have limitations in accurately simulating extreme events. The HYRAS, RADOLAN, and RADKLIM datasets, however, demonstrate a good performance with respect to extremes. As a consequence, these datasets appear to be beneficial for bias adjustments of HRES, though their application is geographically restricted to Germany. The European near real-time OPERA product often underestimates precipitation, while EURADCLIM improves the spatial representation of precipitation patterns in capturing magnitude and extremes. Both IMERG datasets tend to overestimate precipitation magnitudes and extremes, but are improving the spatial accuracy during summer months. As a next step, we plan to implement a machine learning-based bias adjustment into the quasi-operational hydrological forecasting workflow.

**ID: 134, Oral Presentation**

## DeepWaive: A Paradigm Shift in Flood Forecasting through a Hybrid AI Foundation Model

1) Julian Hofmann* (FloodWaive Predictive Intelligence GmbH)

The increasing frequency and severity of extreme precipitation events necessitate innovative approaches to flood forecasting and risk management. Traditional hydrodynamic modeling, while physically robust, faces significant computational constraints that limit its applicability for real-time flood prediction and ensemble-based probabilistic forecasting. This paper presents DeepWaive, a novel hybrid AI foundation model that fundamentally transforms the landscape of flood forecasting.

DeepWaive overcomes the traditional limitations of both hydrodynamic and machine learning approaches through a unique AI foundation architecture that combines the physical understanding of flood processes with the computational efficiency of deep learning. Our model achieves unprecedented processing speeds, enabling the real-time computation of two-dimensional flood inundation mapping with a computational acceleration factor of $10^6$ compared to conventional hydrodynamic models. This breakthrough allows, for the first time, the parallel processing of ensemble precipitation forecasts from the German Weather Service's SINFONY products, enabling probabilistic flood forecasting at previously unattainable spatial and temporal resolutions.

A key innovation of DeepWaive lies in its generalization capabilities. Unlike conventional deep learning models that require retraining for each geographical domain, our approach demonstrates remarkable transferability across diverse topographical and hydrological conditions. This is achieved through extensive training on a comprehensive dataset of hydrodynamic simulations encompassing various geographical and meteorological scenarios. Validation results show that DeepWaive maintains high accuracy levels ($R^2 > 0.9$) across different regions while providing real-time inundation predictions.

The model's capabilities extend beyond pure forecasting to include real-time evaluation of flood protection measures, enabling dynamic assessment of intervention strategies during extreme events. This feature represents a significant advancement in operational flood management, offering decision-makers the ability to rapidly evaluate and optimize response strategies.

These developments mark a significant step forward in flood forecasting and risk management, offering new possibilities for early warning systems and risk mitigation planning. The implementation of DeepWaive demonstrates the potential of AI-driven approaches to address critical challenges in hydrological-hydraulic engineering while maintaining the physical basis necessary for reliable predictions.

**ID: 145, Oral Presentation**

## Development of Flood Level Prediction Model for Hangang Jamsoo Bridge Using Weather Climate Data and Artificial Neural Networks

1) Sung Chul Ha* (Graduate School of Disaster Prevention, Kangwon National University), 2) Byung Sik Kim (Kangwon National University), 3) An Sung Wook (Kangwon National University), 4) Kyung Su Choo

Climate change has increased the frequency and intensity of intense rainfall events and the resulting flood damage is increasing every year. The accurate application of various runoff estimation methods is prone to subjective views among designers and experts. Physical models used for water resource management are difficult to build and require a high level of user understanding, including the selection of parameterization formulas. This can lead to unreliable results depending on the user, which affects the design and dimensional safety of river hydraulic structures. To compensate for these problems, artificial intelligence (AI) is increasingly being utilized. Therefore, in this study, a machine learning model was used to develop a flood level prediction model for the Han River submerged bridge, and the data of July 2011, August 2018, July 2020, August 2020, and July 2022, when heavy rainfall was concentrated, were trained and used for verification in August 2022 and July 2023. A model for predicting the water level of the submerged bridge was built using 10-minute rainfall (AWS Yongsan, Jung-gu, Seongdong, Gwangjin, Seocho, Songpa, Gangdong, and Guri) and Paldam Dam discharge as independent variables, and the water level of the submerged bridge with a 6-hour delay as the dependent variable. The models used for prediction were LSTM (Long Short-Term Memory), an artificial neural network model, and Bi-LSTM (Bi-directional Long Short-Term Memory), and the test results showed that the error of Bi-LSTM was less and the accuracy was higher, evaluating the usefulness of flood level prediction using the Bi-LSTM model.

**ID: 112, Oral Presentation**

### Tailoring SINFONY forecasts and other DWD products to flood forecasting applications following a co-design approach

1) Julia Keller* (Deutscher Wetterdienst), 2) Jan Bondy* (Deutscher Wetterdienst), 3) Vanessa Fundel (Deutscher Wetterdienst), 4) Ina Blumenstein-Weingartz (Deutscher Wetterdienst), 5) Olga Kiseleva (Deutscher Wetterdienst), 6) Maja Rüth (Deutscher Wetterdienst), 7) Stefan Wolff (Deutscher Wetterdienst), 8) Thomas Deutschländer (Deutscher Wetterdienst), 9) Kathrin Feige (Deutscher Wetterdienst), 10) Felix Fundel (Deutscher Wetterdienst), 11) Stefanie Hollborn (Deutscher Wetterdienst), 12) Andreas Lambert (Deutscher Wetterdienst), 13) Armin Rauthe-Schöch (Deutscher Wetterdienst), 14) Ute Badde (State Environmental Agency Baden-Württemberg), 15) Manfred Bremicker (State Environmental Agency Baden-Württemberg), 16) Norbert Demuth (State Environmental Agency Rhineland-Palatinate), 17) Natalie Stahl-van Rooijen (Bavarian Environmental Agency), 18) Joachim Stoermer (Bavarian Environmental Agency)

In recent years, several regions in Germany experienced devastating impacts from heavy precipitation events associated with severe convective storms. To improve the prediction of such events, Deutscher Wetterdienst (DWD) is strengthening its collaboration with Germany´s flood forecasting authorities.
With its focus on the seamless and probabilistic prediction of severe summertime convective events and associated heavy precipitation, DWD´s novel Seamless Integrated Forecasting System (SINFONY) is considered as a major step towards improving precipitation information for the forecast range from minutes to approx. 12 hours. To ensure a significant contribution of the newly developed SINFONY data and products for hydrological applications, in particular the prediction of floods in smaller catchments, the SINFONY Team engages in a continuous dialogue with users from flood forecasting centres. One of the main objectives is to identify user requirements and to utilize this information for targeted development of forecast products. In addition, users are supported in implementing the novel data and products in their models and decision-making processes.
Together with colleagues from regional German Flood Forecasting Centres, a joint project for augmenting the hydrometeorological value chain through co-design was initiated in 2023. The project is part of DWD's new binational research program "Italia – Deutschland science-4-services network in weather and climate", part of which is jointly funded by DWD and the state of Rhineland-Palatinate.
The activities within the "Co-Design Project" stretch across the value chain for the generation of hydrometeorological forecasts. They aim for:

1. a user-oriented evaluation and optimization of DWD's precipitation forecasts (SINFONY, GLORI, ICON-D2-EPS, ...);
2. the implementation of functionalities tailored to the needs of flood forecasting centres into DWD's new warning system;
3. the evaluation of (new) DWD data and products within operational flood forecasting models;
4. the harmonisation and improvement of the communication of precipitation as well as flood forecasts and warnings for a better basis for decision-making.

With this contribution we will provide an overview of the ”Co-Design Project”. It will be accompanied by separate presentations, providing first examples and results on the user-oriented evaluation and communication aspects. We are also interested in an exchange with participants of the PrePEP Conference, working at the intersection of meteorology and hydrology, to learn about their experiences.

**ID: 140, Oral Presentation**

## Developing early warning systems for Greek Prefectures and Municipalities

1) Kostas Lagouvardos* (National Observatory of Athens), 2) Vasiliki Kotroni (National Observatory of Athens), 3) Antonis Bezes (National Observatory of Athens), 4) Theodore Giannaros (National Observatory of Athens), 5) Christos Giannaros (National Observatory of Athens), 6) Athanasios Karagiannidis (National Observatory of Athens), 7) Ioannis Koletsis (National Observatory of Athens)

With the aim to develop early warning systems that meet the needs of prefectures and local communities, the METEO Unit of the National Observatory of Athens has started, during the last two years, to build early warning systems that envelop a multitude of datasets on a web interface that permit to the users to easily assess the current and future weather conditions. These systems are developed in close collaboration with the local authorities to meet their specific needs.
The system includes the installation and operation of a network of meteorological stations as well as the installation and operation of level meters in selected rivers/streams. Satellite data (e.g. precipitation probability) as well as lightning data are also included. Moreover, the early warning system provides high-resolution meteorological forecasts as well as high-resolution fire weather forecasts, and expected conditions on the roads. An automatic generation of warnings sent to the authorities is also implemented, based on predefined thresholds for each category of hazard. The totality of observations and forecasts are provided through a web service. The web service is modular, so additional layers of information can be added in the future.The system is, by definition, a powerful tool for the better information of the authorities and the public before and during a severe weather event. However, the information shown in the early warning system can be used for other activities, such as agriculture, transportation and tourism.

**ID: 139, Poster**

## Predictability plots as a means to assess meteorological input for hydrological models

1) Ina Blumenstein-Weingartz* (Deutscher Wetterdienst), 2) Jan Bondy (Deutscher Wetterdienst), 3) Felix Fundel (Deutscher Wetterdienst), 4) Vanessa Fundel (Deutscher Wetterdienst), 5) Julia H. Keller (Deutscher Wetterdienst)

Flood forecasting strongly relies on the prediction of precipitation. Whenever floods have been observed or they have been (incorrectly) predicted, it is of interest to investigate the underlying forecasts from the different weather models. This can be achieved by predictability plots which summarize the different forecasts with the according lead times for a specific event. A tool to derive predictability plots has been built in the context of the Co-Design project at the German Weather Service (DWD) for the German flood forecasting centers. In this context, the application of the technique onto hydrologic catchment areas creates additional value as those catchments are the same that are used in hydrological runoff models. Extreme value analysis was conducted by the DWD following a method coupled to the AREA product. The resulting return periods for areal precipitation for the catchments are available in the visualization and allow classification of observed and forecast meteorological extreme events. The user can choose a catchment area, the date and time of the event as well as a duration. Ensemble models from the ICON model chain are included in the predictability plots and their role in the prediction of extreme events will be a focus of future investigations as the frequency of forecast high impact events at large lead times might give valuable indications of elevated risks of severe rainfall.

**ID: 69, Poster**

## Predicting hydrological drought in Gangwon the Far East using weather climate data and AI models

1) Ji Hun Park* (AI for Climate & Disaster Management Center, Kangwon National University), 2) Seung Cheol Choi (AI for Climate & Disaster Management Center, Kangwon National University), 3) So Hyun Lee (Kangwon National University), 4) Byung Sik Kim (Department of Artificial Intelligence & Software/Graduate School of Disaster Prevention, Kangwon National University)

In recent years, the frequency and intensity of droughts have been increasing rapidly due to extreme weather events caused by climate change, and this has become a global problem. Traditionally, two indices have been used to assess meteorological drought: the Standardised Precipitation Index (SPI), which considers only precipitation as a variable, and the Standardised Precipitation Evapotranspiration Index (SPEI), which considers both precipitation and evapotranspiration. However, recent droughts have expanded from hypothetical droughts to socio-economic droughts, and the impact on water resources has been recognised as critical. In this study, we aim to develop a model that predicts the SDI (Streamflow drought index), a hydrological drought index based on meteorological climate data, using machine learning. This will contribute to the management of water resources and the establishment of drought response strategies due to climate change.

**ID: 70, Poster**

## Predicting inflows to the Soyang River Dam using Weather climate data and Machine learning

1) Byung Sik Kim* (Department of Artificial Intelligence & Software/Graduate School of Disaster Prevention, Kangwon National University), 2) Seung Cheol Choi (AI for Climate & Disaster Management Center, Kangwon National University), 3) Ji Hun Park (AI for Climate & Disaster Management Center, Kangwon National University)

In recent years, climate change due to global warming has increased the average amount of precipitation and evaporation, and the importance of disaster prevention considering climate change is increasing. Dam inflows must be accurately predicted for dam releases during heavy rainfall and typhoons. Previously, many studies have applied physical models to predict inflow, but recently, with the development of artificial intelligence technology, many studies have applied machine learning-based models. In this study, we collected meteorological and climatic data from meteorological stations upstream of the Soyang River Dam and applied machine learning techniques to predict the inflow of the Soyang River Dam. The data from 2012 to 2023 were collected, and the data from 2012 to 2020 were used as training data to train the models, and the data from 2021 to 2023 were used as validation data. Finally, we applied validation metrics to the prediction results of each machine learning model to compare the prediction results of each model.

**ID: 94, Poster**

## QPE, QPF and EPS in flood forecasting

1) Tobias Heppelmann* (State Environmental Agency Rhineland-Palatinate), 2) Norbert Demuth (State Environmental Agency Rhineland-Palatinate)

Apart from hydrological data (water level and discharge at gauging stations), data on the actual quantitative amount of precipitation (QPE) and predicted precipitation (QPF) are the most important input data in flood forecasting, especially for small catchment areas. Therefore, various approaches of interpolation or radar-based methods are applied to hydrological models in order to arrive at an optimized estimation for the current event.
Depending on regional characteristics (topography, geology, soils, land use, etc.) and the current soil moisture, catchments react more or less sensitively to variabilities in precipitation. The impact of this sensitivity on flood forecasts is taken into account by quantification of uncertainties.
According to analyses of flood events over the last 10 years and R&D projects to improve flood forecasting, examples are presented that reveal the importance of
- recording precipitation as accurately as possible, not only in terms of absolute amounts, but also in terms of spatio-temporal distribution, - ensemble prediction systems (EPS) in flood forecasting, and - quantification of meteorological and hydrological uncertainties.
Based on this, requirements are formulated for the further improvement of Quantitative Precipitation Estimation and Quantitative Precipitation Forecasts regarding flood forecasting, which also demonstrate the relevance of the so-called “Co-design” between weather services and flood forecasting services.

**ID: 101, Poster**

## Rain, Snow or Freezing Rain? – Radar-based Surface Precipitation Type Analysis and Verification at DWD

1) Markus Schultze (Deutscher Wetterdienst), 2) Tim Böhme* (Deutscher Wetterdienst), 3) Jörg Steinert (Deutscher Wetterdienst)

Several years ago, the scope of operational radar-derived precipitation analysis was broadened from precipitation amount by the type of precipitation. Nowadays, areal information on winterly precipitation type and amount are available in near real-time. In addition to providing these data to the general public (e.g. via App), specialized clients like winter road maintenance services benefit from it for optimized operations planning.
The Deutscher Wetterdienst (DWD) utilizes a C-Band weather radar network that provides terrain-following low-elevation scans every five minutes. We apply a common hydrometeor classification scheme using dual-polarimetric radar data and snowline information from NWP. The vertical extrapolation of hydrometeor type from radar beam height to ground level includes the transition from solid to mixed to liquid precipitation phase. These transitions are estimated from empirical thresholds considering wetbulb temperature profiles. In addition to utilizing NWP profiles, station measurements of temperature and humidity are incorporated for optimization within the boundary layer. Recently, we further developed the algorithm to account for supercooling of liquid hydrometeors that reach the ground. The new surface precipitation types "freezing drizzle" and "freezing rain" are operationally used since winter season 2023/2024.
We conduct objective verification of the analyzed precipitation type using measurements of automatic weather stations in Germany. These disdrometer measurements offer continuous data at a high temporal resolution. With approximately 180 stations, the spatial density is adequate to capture the type of stratiform precipitation over flat terrain in many cases. However, in regions with complex topography, the spatial variability in surface precipitation type is not well represented. Additionally, in some cases, technical limitations pose challenges in accurately discriminating between drizzle, light snow and freezing drizzle. In recent years, crowd-soured reports about in situ precipitation type submitted via DWD's WarnWetter-App became increasingly important. Despite user subjectivity, these reports are well-recognized for supporting DWD's warning decision process, particularly during freezing rain events.
This contribution will explain the algorithm using a case study of a complex weather situation in January 2024. Also, recent verification results and challenges in treating various reference data will be discussed.

**ID: 39, Poster**

## Initial Results of Implementing SINFONY Forecast Products in Flood Prediction Using the LARSIM Model at the Flood Forecast Centre of Baden-Württemberg

1) Olga Kiseleva* (Deutscher Wetterdienst), 2) Armin Rauthe-Schöch (Deutscher Wetterdienst), 3) Jan Bondy (Deutscher Wetterdienst), 4) Ute Badde (State Environmental Agency Baden-Württemberg), 5) Thomas Deutschländer (Deutscher Wetterdienst), 6) Manfred Bremicker (State Environmental Agency Baden-Württemberg), 7) Ulla Schwieters (State Environmental Agency Baden-Württemberg), 8) Dominik Elfgang (State Environmental Agency Baden-Württemberg), 9) Julius Weimper (HYDRON Ingenieurgesellschaft für Umwelt und Wasserwirtschaft mbH, Karlsruhe)

The flooding in small catchments in Germany in recent years, driven by locally intense convective precipitation, has caused significant damage and even resulted in fatalities. To ensure accurate, timely, and quantitative operational flood forecasts and warnings, the regional German Flood Forecasting Centres require enhanced precipitation information for short-term forecast ranges. The new Seamless Integrated Forecasting System (SINFONY), developed by the Deutscher Wetterdienst (DWD), was specifically designed to meet the urgent need for seamless and probabilistic predictions of atmospheric conditions, particularly thunderstorms and precipitating cells. The implementation of SINFONY products into flood forecasting models, evaluation of results, optimization of flood warnings, and feedback to developers are key activities supported by the new "Co-Design" research project. This project is jointly developed and conducted by DWD and regional German Flood Forecasting Centres. As part of this collaboration, the Flood Forecast Centre of the State Institute for Environment Baden-Württemberg (HVZ LUBW) has explored the use of meteorological SINFONY data for daily operational discharge forecasts, utilizing the distributed water-balance model LARSIM (Large Area Runoff Simulation Model). This contribution presents evaluation results of simulated floods with exceeded medium probability in small catchments, triggered by small-scale heavy precipitation events that occurred in the southwest of Germany during the summer of 2024.

**ID: 20, Poster**

## Improving Flood Forecasting by Assimilating Remotely Sensed Soil Moisture Data into the ParFlow-CLM Model

1) Samira Sadat Soltani* (Institute of Bio- and Geosciences; Agrosphere (IBG 3), Forschungszentrum Jülich GmbH), 2) Stefan Kollet (Institute of Bio- and Geosciences; Agrosphere (IBG 3), Forschungszentrum Jülich GmbH and University of Bonn)

Accurate hydrologic simulations are crucial for managing water resources and predicting extreme events. However, obvious limitations have emerged following the July 2021 flooding event due to factors like sparse observations and simulation uncertainties related to unknown initial conditions, exacerbated by global warming. To address these limitations, actions are needed, including enhancing observational networks, refining modeling techniques, and integrating knowledge from climate change projections on potential extremes. By overcoming these challenges, we can better prepare for and mitigate the impacts of extreme flooding events. In order to improve the initial value problem, a promising strategy is assimilating satellite-derived soil moisture estimates into hydrological models to reduce uncertainty. However, current data assimilation schemes may neglect the time lag between soil moisture and discharge responses. Ongoing developments focus on implementing more suitable sequential data assimilation methods to address this issue. In this study, an Ensemble Kalman Filter (EnKF) was employed to update model states in the ParFlow-CLM hydrological model. Specifically, soil moisture information derived from the Sentinel1 and ESA-CCI data was assimilated to enhance soil moisture and streamflow estimation. This experiment was conducted at high spatial and temporal resolutions over Germany and neighboring regions during the July 2021 event. The results were validated using the First Order Reliability Method (FORM) which is a novel probabilistic reliability framework. The study underscores the importance of leveraging remote sensing data to improve the accuracy and reliability of flood forecasting systems. By assimilating soil moisture information into integrated terrestrial models, decision-makers can be prepared with timely insights to mitigate flood risks effectively. This research contributes to advancing hydrology and highlights the potential of remote sensing technologies in enhancing resilience to hydrological extremes.

### Acknowledgements

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**ID: 147, Poster**

## Operational High-Resolution Hydrological Forecasting Systems for Short-to-Sub-Seasonal Predictions in Germany

1) Husain Najafi* (Helmholtz Centre for Environmental Research - UFZ), 2) Pallav Kumar Shrestha (Helmholtz Centre for Environmental Research - UFZ), 3) Oldrich Rakovec (Helmholtz Centre for Environmental Research - UFZ), 4) Mehrdad Mohanna Zadeh (Helmholtz Centre for Environmental Research - UFZ), 5) Matthias Kelbling (Helmholtz Centre for Environmental Research - UFZ), 6) Stephan Thober (Helmholtz Centre for Environmental Research - UFZ), 7) Nithila Devi Nallasamy (Helmholtz Centre for Geosciences-GFZ), 8) Sergiy Vorogushyn (Helmholtz Centre for Geosciences-GFZ), 9) Heiko Apel (Helmholtz Centre for Geosciences-GFZ), 10) Bruno Merz (Helmholtz Centre for Geosciences-GFZ), 11) Luis Samaniego (Helmholtz Centre for Environmental Research - UFZ)

Reliable hydrological forecasting across short-to-sub-seasonal (S2S) timescales is vital for flood preparedness and drought early warning. We present two operational forecasting systems developed by the Helmholtz Centre for Environmental Research (UFZ) and partners, targeting impact-based flood forecasting and weekly soil moisture drought outlooks in Germany. The impact-based flood forecasting chain integrates high-resolution numerical weather predictions (ICON-D2/IFS), hydrological simulations via mHM, and hydrodynamic modeling (RIM2D) to generate probabilistic water level and inundation forecasts for selected catchments under the HI-CAM II project. This system was evaluated during the 2021 Ahr Valley flood in a hindcast experiment (Najafi et al. 2024).

Complementarily, the HS2S (High-resolution Short-to-Sub-seasonal Soil Moisture Forecasts) system delivers weekly soil moisture index (SMI) predictions up to six weeks ahead, based on real-time ECMWF ensemble forecasts and post-processed through an automated modeling workflow. These forecasts support drought monitoring efforts such as the German Drought Monitor, operating at 1 km resolution. Both systems represent significant advances in operational early warning capabilities.

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