Conference Program

Karlsruhe Institute of Technology

UNIVERSITÄT BERN
OESCHGER CENTRE

Mobiliar Lab for Natural Risks

Schweizerische Eidgenossenschaft
Confédération suisse
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Eidgenössisches Departement des Innern EDI
Bundesamt für Meteorologie und Klimatologie MeteoSchweiz

MeteoSchweiz

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Supporting bodies:

Karlsruhe Institute of Technology (KIT)
Institute of Meteorology and Climate Research
Troposphere Research (IMKTRO)
Kaiserstraße 12
D-76131 Karlsruhe
https://www.imk-tro.kit.edu

University of Bern
Mobiliar Lab for Natural Risks
Hallerstrasse 12
CH-3012 Bern
https://mobiliarlab.unibe.ch

University of Bern
Oeschger Centre for Climate Change Research
Zähringerstrasse 25
CH-3012 Bern
https://www.oeschger.unibe.ch

Federal Office of Meteorology and Climatology
MeteoSwiss
Operation Center 1
Postfach 257
CH-8058 Zürich-Flughafen
https://www.meteoswiss.admin.ch

Deutscher Wetterdienst (DWD)
Frankfurter Straße 135
D-63067 Offenbach
https://www.dwd.de

Dear Participants of the 4th European Hail Workshop,

In July 2023, northern Italy witnessed two unprecedented European hail records: First, 16-centimeter hailstones were observed, followed by reports of 19-centimeter stones just five days later. But it wasn't just Italy that faced such extreme convective storms in 2023. In the USA and Europe, severe convective storms, accompanied by large hail, caused economic losses exceeding EUR 70 billion — marking yet another record-breaking year. These events incidents raise several questions regarding the impact of climate change on the intensity and frequency of hailstorms, the most effective methods for estimating hail hazard and risk, enhancements of hail detection and forecasting techniques, and optimal strategies for mitigating hail damage. Research endeavors in these areas have yielded significant advancements in recent years, leveraging dedicated field campaigns, improved numerical weather prediction models, and the burgeoning domain of machine learning techniques. Despite these strides forward, our understanding of the underlying drivers of hailstorms, hail growth processes, regional probabilities of hail occurrence, and the associated risks remains incomplete. This knowledge gap underscores the importance of continued collaborative research efforts to enhance our ability to anticipate and mitigate the impacts of hailstorms.

The European Hail Workshop aims to foster the exchange of information on the current state of hail research and to discuss existing deficits and possible solutions in hail modeling and analysis. In addition, this workshop shall also promote networking among scientists and experts in the fields of atmospheric research, weather services, insurance, economics, and agriculture.

We have received an overwhelming response to our call for abstracts. Thanks to your excellent contributions, we are able to present a broad and comprehensive conference program that focuses on various aspects of hail research. The Scientific Steering Committee's evaluation of the abstracts was carried out anonymously to avoid any unconscious biases in the results.

This booklet contains all of the contributions' abstracts. The abstracts of the oral presentations are in chronological order, followed by those of the poster presentations. We would like to thank the Joachim Hertz Foundation for its financial support attempted to foster and intensify the exchange among experienced and early career scientists. The latter will therefore present half of the invited talks.

We would like to extend a very warm welcome to all of you at the 4th European Hail Workshop in Karlsruhe. We are looking forward to interesting presentations and lively discussions.

The organizing committee:

Michael Kunz (KIT), Olivia Romppainen-Martius (Uni Bern), Susanna Mohr (KIT), Alessandro Hering (MeteoSwiss), Katharina Schröer (Uni Freiburg)

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General Information:

Internet access:

At all KIT locations, you can get Internet access via “eduroam”. “eduroam” is an international Wi-Fi Internet access roaming service of universities and research institutions. KIT has been a member of the eduroam network since its inception.

At KIT (and some places in the city of Karlsruhe) you can also get access via the open and unencrypted network “KA-WLAN”. For a secure access, you can use the “KA-sWLAN”. This requires a registration at https://www.ka-wlan.de/register/.

Networking rooms at free disposal:

A seminar room is available for individual discussions between workshop participants. If you are interested, please contact the registration desk.

Programme overview:

4th European Hail Workshop: 5 March – 7 March 2024

as of 28 February 2024

Time CET: 09:00 – 20:30

Tuesday	Wednesday	Thursday
from 11:30 | Registration open	09:00 – 10:15 Session 3b (5 Talks) Hail climatology, risk, and loss	09:00 – 10:30 Session 6b (6 Talks) Hail detection and forecasting
12:15 – 12:30 Opening (incl. technical infos)	10:15 – 10:45 Break	10:30 – 11:00 Break
12:30 – 14:10 Session 1a (6 Talks) Convection and hail in a changing climate	10:45 – 11:50 Session 4 (4 Talks) Hail research and AI/ML	11:00 – 12:00 Session 6c (4 Talks) Hail detection and forecasting
14:10 – 14:40 Break	11:50 – 12:05 Session 5a Field campaigns (1 Talk)	12:00 – 12:30 Early career panel discussion Teaching & research in meteorology in the time of AI/ML
14:40 – 15:10 Session 1b (2 Talks) Convection and hail in a changing climate	12:05 – 13:15 Lunch break	12:30 – 13:30 Lunch break
15:10 – 16:30 Session 2 (5 Talks) Hail damage and damage prevention	13:15 – 14:00 Poster pitches	13:30 – 15:05 Session 7a (6 Talks) Microphysics and dynamics of hail storms
16:30 – 17:00 Break	14:00 – 15:45 Poster session	15:05 – 15:35 Break
17:00 – 18:35 Session 3a (6 Talks) Hail climatology, risk, and loss	15:45 – 16:00 Break	15:35 – 17:20 Session 7b (7 Talks) Microphysics and dynamics of hail storms
	16:00 – 17:05 Session 5b (4 Talks) Field campaigns	17:20 – 17:30 Closing remarks
	17:05 – 17:25 Break	
	17:25 – 17:55 Panel discussion Collecting new data through field campaigns	
	17:55 – 18:30 Session 6a (2 Talks) Hail detection and forecasting	
	18:30 Get together (Foyer Tullahörsaal)	

Conference Programme

4th European Hail Workshop | 5 March – 7 March 2024

as of 26 February 2024

Tuesday, 5 March 2024

from 11:30	**Registration**
12:15	**Conference start (KIT, Building 11.40, Tulla Lecture Hall)**
12:15 – 12:30	**Michael Kunz (KITy), Olivia Romppainen-Martius (Univeristy of Bern), Susanna Mohr (KIT)** Welcome, Opening remarks & Technical Infos
Session 1a: Convection and hail in a changing climate	
12:30 – 12:50	**Invited: Lasher-Trapp, Sonia (University of Illinois), Holly Mallinson, Robert J. Trapp, Matthew Woods, Sophie Orendorf** Hailfall in a future climate using a pseudo-global warming approach
12:50 – 13:10	**Invited: Mateusz Taszarek (Adam Mickiewicz University), Tomáš Púcik, John T. Allen** Common environmental features associated with large hail across Australia, Europe and the United States
13:10 – 13:25	**Timothy Raupach (University of New South Wales), Raphael Portmann, Christian Siderius, Stephen Sherwood** Global projections of hail hazard frequency under climate change
13:25 – 13:40	**Agostino Manzato (APRA FVG), Gabriele Fasano, Andrea Cicogna, Francesco Sioni, Arturo Pucillo** Are the relationships between environmental parameters and storm observations climate-change invariant?
13:40 – 13:55	**Francesco Battaglioli (ESSL), Pieter Groenemeijer, Mateusz Taszarek, Tomáš Púcik, Anja Rädler** Modeled multidecadal trends of (very) large hail in Europe, the United States and globally
13:55 – 14:10	**Anton Schulte-Fischedick (Universität Freiburg), Katharina Schröer** Variability and indication of change in convective storm patterns in the Western Alpine region: A storm-based analysis utilizing 20 years of observation
14:10 – 14:40	**Coffee Break (Tulla hall)**
Session 1b: Convection and hail in a changing climate	
14:40 – 14:55	**Iris Thurnherr (ETH Zurich), Patricio Velasquesz, Ruoyi Cui, Killian Brennan, Lena Wilhelm, Heini Wernli, Christian R. Steger, Christoph Schär** The effect of 3 °C global warming on hail in Europe
14:55 – 15:10	**Abdullah Kahraman (Newcastle University), Elizabeth J. Kendon, Hayley Fowler** Exploring future hailstorms and convective storm features across Europe using km-scale simulations
Session 2: Hail damage and damage prevention	
15:10 – 15:30	**Invited: Luis Ackermann (Bureau of Meteorology), Joshua Soderholm, Alain Protat, Rhys Whitley, Lisa Ye, Nina Ridder** Radar and environment-based hail damage estimates using machine learning
15:30 – 15:45	**Simon Eng (University of Western Ontario), Julian Brimelow, Gregory Kopp** Forensic post-storm investigations of hailstorms and their impacts
15:45 – 16:00	**Brenna Meisenzahl, Bryn Ronalds (Insurance Institute for Business and Home Safety)** Sub-severe hail: The missing piece in assessing property risk in North America
16:00 – 16:15	**Raphael Portmann (Agroscope,), Timo Schmid, Leonie Villiger, David N. Bresch, Pierluigi Calanca** Modelling crop hail damage footprints with single-polarization radar
16:15 – 16:30	**Mirjam Hirt (Munich RE), Anja Rädler, Jana Löffelmann, Thomas Hofherr, Peter Miesen, Alex Allmann** Hail diameter footprints and simulations of hail damages

16:30 – 17:00	**Coffee Break (Tulla hall)**
Session 3a: Hail climatology, risk, and loss	
17:00 – 17:20	**Invited: Leonie Villinger (ETH Zurich), Martin Aregger, Killian Brennan, Pierluigi Calanca, Ruoyi Cui, Olivia Martius, Raphael Portmann, Christoph Schär, Timo Schmid, Iris Thurnherr, Patricio Velasquez, Heini Wernli, Lena Wilhelm, David N. Bresch** Seamless coupling of kilometer-resolution weather predictions and climate simulations with hail impact assessments for multiple sectors (scClim)
17:20 – 17:35	**Vera Meyer (Geosphere Austria), Gregor Ehrensperger, Marc Falkensteiner, Tobias Hell, Georg Pisotnik, Lukas Tüchler, Hildegard Kaufmann** New hail hazard map for Austria
17:35 – 17:50	**Jannick Fischer (KIT), Matthew Kumjian, Kelly Lombardo, Michael Kunz** How do updraft width, intensity, and water content influence hail size in toy simulations?
17:50 – 18:05	**Henry M. Wells (Loughborough University), John Hillier, Freya K. Garry, Nick Dunstone, Huili Chen, Mateusz Taszarek** Environment and convective mode of severe hail-producing storms in the United Kingdom
18:05 – 18:20	**Lena Wilhelm (Uni Bern), Olivia Martius, Cornelia Schwierz, Katharina Schröer** Hail in Switzerland – Modeled trends, decadal variability, and large-scale drivers
18:20 – 18:35	**Timo Schmid (ETH Zurich), Raphael Portmann, Leonie Villinger, Katharina Schröer, David N. Bresch** Radar-based hail damage modelling for buildings and cars in Switzerland: Model evaluation and ways forward

Wednesday, 6 March 2024

Session 3b: Hail climatology, risk, and loss	
09:00 – 09:15	**Hans Feyen (Schweizer Hagel)** Practical use of hail climatology in crop insurance
09:15 – 09:30	**Charles Jackson (Verisk), Alex Sokolowsky, Greg Bopp, Boyko Dodov** A new global model framework for representing weather systems responsible for observed hail occurrence over the US and Europe
09:30 – 09:45	**Subin Thomas (Moddy'S RMS), Kieran Pope, Phil Haines, Juergen Grieser** Comparison of ML models to create hail risk in the Contiguous United States
09:45 – 10:00	**Punit Bhola (Verisk), Caroline McMullan, Alexander Doyle, Harsh Mistry, Stefanie Alarcon, Bernhard Reinhardt, Shane Latchman** A comprehensive review of recent catastrophic hail events and their impacts on the insurance industry
10:00 – 10:15	**Stefan P. Ritz (RenaissanceRE), David R. Bachiochi, David Hamilton** Considering climate change and natural climate variability when comparing stochastic hail loss model output against recent loss history
10:15 – 10:45	**Coffee Break (Tulla hall)**
Session 4: Hail research and AI/ML	
10:45 – 11:05	**Invited: John T. Allen (Central Michigan University), Cameron Nixon, Tobias Schmidt, Amy McGoven, Corey Potvin, Randy Chase, John Williams, Cameron Homeyer, Benjamin Scarino, Kyle Itterly, Kris M. Bedka, Kyle Gillett, Mateusz Taszarek** Leveraging machine learning and AI in hail prediction and forecasting
11:05 – 11:20	**Martin Lainer (MeteiSwiss), Killian P. Brennan, Alessandro Hering, Jérôme Kopp, Samuel Monhart, Jannis Portmann, Daniel Wolfensberger, Urs Germann** Drone-based photogrammetry combined with deep-learning to estimate hail size distributions and melting of hail on the ground
11:20 – 11:35	**Alfonso Ferrone (EPFL), Jérôme Kopp, Martin Lainer, Matteo Guidicelli, Marco Gabella, Urs Germann, Alexis Berne** Double moment normalization of the number distributions of hail size over Switzerland
11:35 – 11:50	**Boris Blanc (ETH Zurich), Andreas Prein, Ulrike Lohmann, Neil Aellen** Improving our understanding of hail hazards using machine learning

Session 5a: Field campaigns	
11:50 – 12:05	**Joshua Soderholm (Bureau of Meteorology), Matthew Kumjian, Julian Brimelow, Michael Kunz, Silke Trömel** Observations of hailstone-like trajectories and growth
12:05 – 13:15	**Lunch Break (Tulla hall)**
13:15 – 14:00	**Poster pitches (Tulla Lecture Hall)**
14:00 – 15:45	**Poster session (Tulla hall)**
15:45 – 16:00	**Coffee Break (Tulla hall)**
Session 5b: Field campaigns	
16:00 – 16:20	**Invited: Julian Brimelow (University of Western Ontario), Gregory Kopp, Simon Eng** Unravelling the mysteries of hail
16:20 – 16:35	**Michael Kunz (KIT), Elias Hühn, Jannick Fischer, Susanna Mohr, Melissa Latt, Silke Trömel, Joshua Soderholm** Enhancing insights into large hail formation and trajectories through targeted field campaigns
16:35 – 16:50	**Ian Giammanco, Tanya Brown-Giammanco** The IBHS field research program: Over a decade of observing hail and hailstorms
16:50 – 17:05	**Carme Farnell (Servei Meteorològic de Catalunya), Tomeu Rigo, Javier Martín-Vide** Going inside of hailstones from a giant hail event in Catalonia
17:05 – 17:25	**Coffee Break (Tulla hall)**
17:25 – 17:55	**Panel discussion: The truth aloft: Collecting new data through field campaigns. A community exchange on ongoing and planned field projects** Panellist: Becky Adams-Selin, Julian Brimelow, Pieter Groenemeijer, Robert J. Trapp
Session 6a: Hail detection and forecasting	
17:55 – 18:15	**Invited: Ulrich Blahak (DWD) and the SINFONY Team** Current status of SINFONY – The combination of nowcasting and numerical weather prediction on the convective scale at DWD
18:15 – 18:30	**Michael Debertshäuser (DWD), Paul James** Integrating KONRAD3D into the nowcasting guidance system NowCastMIX at DWD
18:30	**Get-Together (Tulla hall)**

Thursday, 7 March 2024

Session 6b: Hail detection and forecasting	
09:00 – 10:30	**Alessandro Hering (MeteoSwiss), Luca Nisi, Martin Aregger, Marco Boscacci, Lorenzo Clementi, Urs Germann** Improvements of the object-based nowcasting system TRT for automatic thunderstorm and hail warnings in the Alpine area
09:15 – 09:30	**Vito Galligani (CIMA-IFAECI), Maite Cancelada, Paola Salio, Sarah Bang, Hernán Bechis** Testing a spaceborne passive-microwave severe hail retrieval over Argentina using ground-based dual-polarization radar
09:30 – 09:45	**Jérôme Kopp (Uni Bern), Alessandro Hering, Urs Germann, Olivia Martius** Investigating hail remote detection accuracy: A comprehensive verification of radar metrics with 150’000 crowdsourced observations over Switzerland
09:45 – 10:00	**Tomáš Púcik (ESSL), Mateusz Taszarek, Pieter Groenemeijer, Francesco Battaglioli** Pre-storm environments and storm-scale properties of the major hailstorms of 2021, 2022 and 2023 in Europe
10:00 – 10:15	**Robert J. Trapp (University of Illinois), Gabrielle Christo, Melinda Berman, Stephen Nesbitt, Larry Di Girolamo, Edward Wolff** Satellite-based quantification of convective updraft characteristics: Application to hail severity
10:15 – 10:30	**Martin Aregger (Uni Bern), Olivia Martius, Alessandro Hering, Urs Germann** Differential reflectivity columns and hail-linking C-band radar-based estimated column characteristics to a uniquely large dataset of crowdsourced surface observations in Switzerland
10:30 – 11:00	**Coffee Break (Tulla hall)**
Session 6c: Hail detection and forecasting	
11:00 – 11:15	**Vinzent Klaus (University of Natural Resources and Life Sciences), John Krause** Updraft characteristics of hailstorms and their utility in hail size nowcasting
11:15 – 11:30	**Monika Feldmann (Uni Bern), Daniela I.V. Domeisen, Olivia Martius** Investigating the predictability link between heatwaves and severe convective outbreaks in Europe
11:30 – 11:45	**Minda Le (Colorado State University), V. Chandrasekar** Global hail distribution as observed by GPM DPR
11:45 – 12:00	**Francesco De Martin (University of Bologna), Agostino Manzato, Nicola Carlon, Federico Pavan, Sebastiano Carpentari, Guido Cioni, Mario Marcello Miglietta** European record-breaking hailstorms in northern Italy on 19 and 24 July 2023
12:00 – 12:30	**Early career panel discussion: Teaching and research in meteorology in the time of AI** Panellist: Monika Feldmann, Vincent Forcadell, Yuzhu Lin
12:30 – 13:30	**Lunch Break (Tulla hall)**
Session 7a: Microphysics and dynamics of hail storms	
13:30 – 13:20	**Invited: Annette Miltenberger (Uni Mainz)** Impact of initial condition and cloud physics perturbations on predictions of convective storms and associated hail
13:50 – 14:05	**Mathias Gergely (DWD), Michael Frech, Friedrich Seeger** Exploiting DWD's operational C-band radar birdbath scan for quantifying hail characteristics
14:05 – 14:20	**Andrew Heymsfield (NCAR), Miklos Szakall, Alexander Theis** A Wind Tunnel IA wind tunnel investigation of the melting of hailstones – Part II: Implications for hailstone size distributions measured at the ground
14:20 – 14:35	**Yuzhu Lin (Pennsylvania State University), Matthew Kumjian** Implementing physical assumptions about nonspherical hailstone shapes
14:35 – 14:50	**Sarah Bang (NASA Marshall Space Flight Cent)** Spaceborne remote sensing of hail: Retrievals, climatologies, and challenges going forward
14:50 – 15:05	**Killian P. Brennan ETH Zurich), Heini Wernli, Michael Sprenger, André Walser, Marco Arpagaus** A modeling case study of a severe hail storm in complex topography
15:05 – 15:35	**Coffee Break (Tulla hall)**

Session 7b: Microphysics and dynamics of hail storms	
15:35 – 15:50	**Patrick Kuntze (Uni Mainz), Corinna Hoose, Michael Kunz, Lena Frey, Annette Miltenberger** Impact of aerosol and microphysical uncertainty on the evolution of a severe hailstorm
15:50 – 16:05	**Xiaofei Li (Northwest University)** CCN effects on hail and its uncertainty evaluation compared with initial meteorological condition
16:05 – 16:20	**Xiangyu Lin, Haifan Zhang, Qinghong Zhang, Andrew Heymsfield** Isotopic analysis for tracing vertical growth trajectories of hailstones
16:20 – 16:35	**Johanna Seidel (KIT), Alexei Kiselev, Susan Hartmann, Frank Stratmann, Alice Keinert, Thomas Leisner** Hailstones falling through a cloud of supercooled droplets: No evidence of efficient ice multiplication
16:35 – 16:50	**Becky Adams-Selin (Verisk), Conrad Ziegler** The impact of hailstone shape on hail trajectory stochasticity
16:50 – 17:05	**Hannah Vagasky (Verisk), Becky Adams-Selin, Sarah Bang, Andrew Heymsfield, Aaron Bansemer, Sarah Stough, Andrew Detwiler** An Exploration of Hail Melt Sensitivities Using Hail Trajectory Models and Observations
17:05 – 17:20	**Anthony Crespo (University of Wisconsin-Madison), Angela Rowe, Lucia E. Arena, William O. Nachlas** Characterizing hailstones from different storm modes: A novel method for analyzing physicochemical properties of non-soluble particles in hailstones
17:20 – 17:30	**Closing remarks**

Poster session (Wednesday, 06 March 2024 14:00 – 15:45)

	Session 1: Convection and hail in a changing climate
02	**Tomeu Rigo (Servei Meteorològic de Catalunya), Carme Farnell** Identification of the causes in the increase of hail records in Catalonia since 2010
	Session 2: Hail damage and damage prevention
03	**Denislav Bonchev (Stroyproject Ltd), Tsvetelina Dimitrova, Rumjana Mitzeva** A case study of the evolution of severe hail thunderstorm developed over Bulgaria on 06 August 2023 in relation to hail suppression
04	**Nadezhda Kadiyska, Tsvetelina Dimitrova (Hail Suppression Agency), Denislav Bonchev and Rumjana Mitzeva** Analysis of radar characteristics of seeded and non-seeded hail cells developed over Bulgaria
05	**Jana Löffelmann (Munich Re), Thomas Hofherr, Anja Rädler, Mirjam Hirt, Peter Miesen, Alex Allmann** Developing a synthetic hail event set for risk assessment
06	**Julijana Nadj, Đorde Kardum (TRAYAL Corporation), Dragana Vujovic, Jovan Janevski (TRAYAL Corporation)** Damage to crops caused by hail in Serbia
07	**Đorde Kardum (TRAYAL Corporation), Zoran Babic, Julijana Nadj, Jovan Janevski (TRAYAL Corporation)** Automation of the hail suppression system in Serbia
08	**Satyanarayana Tani (Graz University of Technology)** Sharing insights from coordinating and recent developments in hail defence operations in Styria Province, Austria
	Session 3: Hail climatology, risk, and loss
09	**Andreas Muehlbauer (FM Global)** Global hail hazard modeling framework
10	**Stella Berzina, Lena Wilhelm, Martin Aregger (Uni Bern), Olivia Martius** Co-occurrence of hail and heavy precipitation in Switzerland
11	**Lilia Bocheva (1National Institute of Meteorology and Hydrology), Krastina Malcheva, Radoslav Evgeniev** Recent spatial distribution and frequency of hail precipitation in Bulgaria
12	**Jannick Fischer (KIT), Kris M. Bedka, Michael Kunz** Hail climatology, trend, and hazard models for South America and Australia
13	**Susanna Mohr (KIT), Michael Kunz (KIT)** An updated 3D radar-based hail statistic for Germany (2005 – 2023)
14	**Sioutas Michalis** Thunderstorm-hailstorm relationships and hailswath characteristics in Greece
	Session 4: Hail research and AI/ML
15	**Denislav Bonchev (Stroyproject Ltd), Nikolay Penov, Martin Slavchev, Tsvetelina Dimitrova, Guergana Guerova** Machine learning algorithm for hail nowcasting in Northwest Bulgaria
16	**Monika Feldmann (Uni Bern), Louis Poulain-Auzéau, Milton Gomez, Tom Beucler, Olivia Martius** Convective environments in AI-models – What have Panguweather, Graphcast and Fourcastnet learned about atmospheric profiles?
17	**Paula Bigalke (University of Cologne), Claudia Acquistapace, Daniele Corradini** Investigation of climatic changes for hail storms over the Alps using spatiotemporal satellite imagery and self-supervised machine learning
18	**Ge Qiao (Peking University), Qinghong Zhang** Construction and feature analysis of surface hail report data set in China based on crowdsourcing
19	**Vincent Forcadell (Météo-France, CNRM), Clotilde Augros , Olivier Caumont** Towards using artificial intelligence to estimate the occurrence and size of hail? Progress and challenges with the French dual-polarization radars

Session 6: Hail detection and forecasting	
20	**Becky Adams-Selin (Verisk), Chase Calkins** Environments associated with hail production in subtropical South America
21	**Pieter Groenemeijer, Francesco Battaglioli (European Severe Storms Laboratory), Tomáš Púcik** Stormforecast.eu: Real-time automated forecasts for hail and lightning based on post-processed NWP
22	**Hernán Bechis (University of Buenos Aires), Bruno Zanetti Ribeiro, Paola Salio** Analysis of convective parameters associated with hail reports from the South American meteorological hazards and their impacts database
23	**Mark Gartner, Julian Brimelow (University of Western Ontario)** The effectiveness of a continuous-wave radar to measure the fall speed of hailstones
24	**Orietta Cazzuli (ARPA Lombardia), Luca Baldini, Roberto Cremonini, Antioco Vargiu, Giulio Camisani, Gian Paolo Minardi, Renzo Bechini** Hail monitoring in Milan district by a network of dual-polarization X-band weather radars
25	**Stefan Georgiev (Hail Suppression Agency), Denitsa Barakova** Wind shear as a predictor of severe and non-severe hail – Preliminary results from Bulgaria in 2018 – 2023
26	**Mateusz Taszarek (Adam Mickiewicz University), Bartosz Czernecki, Piotr Szuster** ThundeR – A rawinsonde package for processing convective parameters and visualizing atmospheric profiles
27	**Markus Schultze (DWD), Tabea Wilke, Christian Berndt** Radar-based hail detection and hail size estimation at DWD
28	**Yi-Xuan Shou (National Satellite Meteorological Center), Lu Feng, Haibo Zhao** Deriving Hail likelihood from Fengyun-4 satellite observations using an ensemble machine learning method
29	**Jake Sorber (IBHS), Rafi Marandi, Ian Giammanco, Aaron Prabhakaran** Development of an omni-directional disdrometer for detection of wind-driven hail
30	**Arne Spitzer (DWD), Ulrich Blahak, Matthias Jerg, Harald Kempf, Manuel Werner** Using crowdsourced data to verify object-based nowcasting
31	**Valentina Campana (ARPA Piemonte), A. Fornasiero, Roberto Cremonini, P.P. Alberoni** Identification of large hail using weather radar data in Piemonte and Emilia-Romagna regions
32	**Tomeu Rigo, (Servei Meteorològic de Catalunya,) Carme Farnell** A radar analysis of two giant hail thunderstorms in Catalonia
33	**Cloé David (Météo-France, CNRM), Clotilde Augros, François Bouttier, Benoît Vié** Preliminary findings on the links between ZDR columns and hail in France
Session 7: Microphysics and dynamics of hail storms	
34	**Carme Farnell (1Servei Meteorològic de Catalunya), Tomeu Rigo, Andy Heymsfield** The different shapes of hailstones depending on the thermodynamics.
35	**Agostino Manzato, Charles Knight, Matthew Kumijan, Barbara Stenni, Giuliano Dreossi, Mauro Masiol, Qinghong Zhang, Xiangyu Lin, Andrew Heymsfield** A comprehensive description of first August 2021 hailstorm in Azzano Decimo, NE Italy
36	**Katerina Skripniková (Czech Academy of Sciences), Zbynek Sokol** Evolution of severe hailstorms as observed by polarimetric X-band radar at the Milešovka observatory
37	**Miklos Szakall (Uni Mainz), Alexander Theis, Andrew Heymsfield, Subir Kumar Mitra, Waldemar Schledewitz, Stephan Borrmann** Comparative study into the melting of spherical and natural-like hailstones
38	**Alexander Theis (Max Planck Institute for Chemistry), Laura Gömmer, Laura Werner, Subir Kumar Mitra, Andrew Heymsfield, Stephan Borrmann, Miklos Szakall** A wind tunnel investigation on the heat and mass transfer of hailstones
39	**Haifan Zhang (Peking University), Xiangyu Lin, Qinghong Zhang, Kai Bi, Chang-Pang Ng, Yangze Ren, Huiwen Xue, Li Chen, Zhuolin Chang** Analysis of insoluble particles in hailstones in China

Panel discussion

The truth aloft: Collecting new data through field campaigns – A community exchange on ongoing and planned field projects

Wednesday, 6 March 2024
17:25 – 17:55

One of our two panel discussions is dedicated to the topic of field campaigns. Data measured in real environments are a cornerstone of our knowledge. Such data serve as an indispensable reference for the model world, but are also needed to produce, validate, and develop further long-term data series from persisting observation systems.

What insights have been gained in previous measurement campaigns around the world, and what advice do experienced field researchers have for those planning future measurement campaigns? What are the most pressing scientific questions that we hope to answer with on-site measurement data? What measurements and data do the communities from modelers to impact specialists require? To find answers to these questions, our discussion will bring together experienced experts on the panel but will also involve the community in an open discussion. We look forward to a stimulating exchange very close to the turbulent heart of the hailstorms.

Panelist:
Becky Adams-Selin (Verisk Atmospheric and Environmental Research)
Julian Brimelow (University of Western Ontario)
Pieter Groenemeijer (European Severe Storms Laboratory)
Robert J. Trapp (University of Illinois Urbana–Champaign)

Moderation:
Jannick Fischer (Karlsruhe Institute of Technology)

Early career panel discussion

Teaching and research in meteorology in the time of AI/ML

Thursday, 7 March 2024
12:00 – 12:30

In the past year, ground-breaking progress has been achieved in AI-based weather prediction and forecasting. This begs the question of how the education and training of young meteorologists and atmospheric scientists need to be adapted to these developments. We plan to gather opinions, ideas, needs, and suggestions on this important topic.

Panelist:
Monika Feldmann (University of Bern)
Vincent Forcadell (Météo-France/Centre National de Recherches Météorologiques)
Yuzhu Lin (The Pennsylvania State University)

Moderation:
Martin Aregger (University of Bern)
Lena Wilhelm (University of Bern)

Hailfall in a future climate using a pseudo-global warming approach

Sonia Lasher-Trapp[1], Holly Mallinson[1], Robert J. Trapp[1], Matthew Woods[1], Sophie Orendorf[1]

[1]University of Illinois Urbana–Champaign, United States

Despite the advances in understanding possible changes to convective environments under anthropogenic climate change from multiple studies, a direct correlation between anticipated increases in convective storm strength in future storms and implications for hailfall has remained tenuous, in part because bulk environmental parameters exhibit little skill in predicting hail size at the ground.

In this study, we have employed an event-level "pseudo-global-warming" (PGW) framework to simulate seven past hailfall events. They occurred over multiple regions in the United States, over a variety of seasons, and include a range of hailfall at the ground. These events are simulated at high resolution both in their historical environment as well as in a PGW environment, the latter modified by end-of-century predictions from five different global climate models.

A comparison of historical and PGW simulations for each event show seasonal differences. Nearly all PGW simulations had only mildly stronger updrafts compared to the historical simulations, but the cold-season PGW simulations showed increases in hail sizes both within the storms and at the surface compared to the historical simulations. On the other hand, warm-season PGW simulations exhibited a decrease in hail sizes at the surface and within the storms compared to the historical simulations. This result might be explained by a stronger warm-rain process in the warm-season events that produced a greater number of hail embryos competing for supercooled liquid water in their PGW simulations.

Cold-season events also had increased event total hailfall area at the ground in their PGW simulations. The PGW simulations of warm-season events exhibited decreases in hailfall area, but increased melting depths likely contributed to a greater event-level rainfall area for those events, where an increase in smaller hail aloft was more prone to melting.

Common environmental features associated with large hail across Australia, Europe and the United States

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It is well known that atmospheric environments across Australia, Europe and the United States are conducive to the occurrence of convective storms resulting in significant tornadoes, giant hail and damaging winds. However, while many studies have focused on specific regions, only a limited number of elaborations compared different parts of the world. Therefore, in this work we use severe weather reports, lightning data and ERA5 reanalysis over the last 20 years to address the following research question: Do severe storms across Australia, Europe and the United States share environmental similarities? A comparison of vertical profiles of temperature, moisture and wind highlighted several features that are common for specific hazards among all three continents. In the context of large hail it was: (1) enhanced negative parcel buoyancy between $-10\,^{\circ}$C and $-40\,^{\circ}$C, (2) strong low-level storm-relative winds, (3) strong 1 – 3 km or 1 – 6 km vertical wind shear, (4) weak low-level environmental winds and vertical wind shear, (5) high lifted condensation level and reduced low-level relative humidity, and (6) some convective inhibition to promote isolated convective mode. We also found that low-level moisture flux along with near-ground storm-relative helicity and streamwise vorticity was the best discriminator between significant tornadoes and very large hail events. However, despite these similarities, statistical analysis indicated that a predictive value of some ingredients can be markedly different among continents. A prime reason for that are different underlying climatological conditions. For example, steep mid-tropospheric lapse rates turned out to be excellent predictor for large hail in the United States, but much worse over Europe and Australia. For this reason, we believe that developing environmental models intended to work universally across different parts of the world can be extremely difficult as it might be challenging to disentangle signals associated with physical processes from those driven by a local climatology.

Global projections of hail hazard frequency under climate change

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Hailstorms regularly damage assets, raze crops, and harm people. A single hailstorm can cause more than USD $1b in damages, and hail is a significant contributor to insured losses in many areas. However, how hailstorms may change under global warming remains uncertain, with large geographical differences in observed and modeled trends and sparse data in large regions. Here, we show proxy-based projections for changes in the occurrence frequency of hail-prone atmospheric environments worldwide. The projections are made using a selection of CMIP6 models, and compare historical environments to those from a future scenario with two and three degrees Celsius of global warming. The proxy applied to the historical period is able to identify known hail-prone regions and matches well with results from global reanalysis data. Future changes depend on world region but show spatial and temporal shifts in hail hazard. We examine changes to the hail threat to crop regions globally by analyzing changes in hail-prone environment frequency during crop growth seasons, using a high-resolution dataset of crop areas and growing periods. These projections help to reduce the uncertainty around possible changes to hail hazard and its impacts in a warming climate.

Are the relationships between environmental parameters and storm observations climate-change invariant?

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For climate models, forecasting environmental parameters is easier than explicitly predicting storm activity, including lightning flashes, hail at ground and accumulated convective rainfall. It is common to identify – on past data – some statistical relationships between environmental parameters, that favor storm occurrence or intensification, and storm-related observations. Then, these relationships are applied to future model scenarios.

In this study, many environmental parameters derived from radiosounding observations in Northeastern Italy are studied during the 1992 – 2022 convective seasons (April – September), and their changes in this 31-year period are assessed. For instance, the temperature shows an increase of approximately 0.53 °C every 10 years (as average across different mandatory levels), while the precipitable water exhibits a positive trend of about 13 % per degree Celsius (with the saturation vapor pressure increasing on average 7.7 % per degree Celsius). Most of the examined indices, particularly those linked to water content, wind shear and potential instability, are characterized by a noticeable upward trend, that should potentially favor the formation and intensification of storms, hail and rainfall. However, upon studying corresponding local storm-related observations, similar trends do not clearly emerge. Instead, mostly statistically non-significant trends are discovered for rain, lightning and hail. The only clear trend indicating more severe events is the one found for the median of the hailstone diameter distribution per hailpad. This result fits well with the increasing trend of CAPE/updraft (that should produce larger hailstones) and higher wet bulb zero-level in the cloud (that should favor the melting of small hailstones).

In conclusion, finding a statistical relationship between more favorable environmental parameters and the observed convective events is not straightforward. In fact, the development of convective storms is a highly complex phenomenon, and simple statistical relationships with average environmental conditions could miss some of the underlying mechanisms. In practice, the relationships between environmental parameters and storm development are not climate-change invariant, at least at the local scale of Northeastern Italy, shading new light on the consideration of future storms in the perspective of global warming.

Modeled multidecadal trends of (very) large hail in Europe, the United States and globally

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Additive Logistic Regression Models for (very) large hail were developed across Europe and the United States using lightning observations, hail reports and convective parameters from the ERA5 reanalysis. In order to model hail, convective initiation was taken explicitly into account meaning that, P_{hail} (probability of hail) was computed as the product probability of P_{storm} (probability of convective initiation) and $P_{hail|storm}$ (conditional probability of hail given a storm). The statistical models were applied to the ERA5 reanalysis to reconstruct the probability of lightning, large and very large hail from 1950 to 2021, at one hourly intervals, across Europe and the United States. Summing these probabilities, we obtained mean climatological distributions that are in strong agreement with observed patterns and can accurately resolve local-scale features thanks to the high spatial resolution of the ERA5 reanalysis. In addition, using the full 72-year time series we analyzed long-term trends, detecting important differences among the two regions of interest. Across the United States, 1950 – 2021 hail trends were found to be weak and mostly non-significant. In Europe, trends are generally positive and significant with northern Italy standing out as a hotspot. Here, the convective activity has seen an abrupt increase with very large hail being 3 times more likely in recent years (2012 – 2021) than it was in the 1950s. The models were then trained simultaneously across Europe, the United States and Australia to yield a more globally applicable hail model. The resulting global modeled hail climatology and the associated long-term trends will be presented. The relationship between modeled changes in hail frequency and observed changes in insured losses across different regions of the world will also be explored.

Variability and indication of change in convective storm patterns in the Western Alpine region: A storm-based analysis utilizing 20 years of observation

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Hailstorms occur frequently in the Western Alpine region, with record damage in recent years. This study expands on previous hail climatologies by investigating spatio-temporal patterns of different hailstorm types based on 63'416 identified storms and recently reprocessed radar hail data spanning two decades (MeteoSwiss, 2002 – 2021). Although this time frame is too short to derive robust trends on the climatological time scale, we argue that the database allows us to explore whether observed storm patterns align with expected changes in severe convective storms and results from studies on large-scale convective environments. We derived conceptual storm types (single-cell, multi-cell, squall-line) by a threshold-based classification of hailstorm attributes and proxies for storm interaction alongside a Random Forest Classifier to identify supercells, using data from the mesocyclone detection algorithm by Feldmann et al. (2021). As conceptual storm types are ambiguous, we further classified storm types using a Gaussian Mixture Model. The storm attributes temporal development was assessed through quantile regression and preliminary results measured as a percentage change in the fitted values between 2002 and 2021.

Generally, quantile changes were coherent throughout the distribution but more pronounced in lower quantiles (10th, 25th) as opposed to higher ones (75th, 90th). Exclusively, storm velocity exhibited a concurrent increase (10th, 46 %) and decrease (90th, −13 %). Meanwhile, the median increased for hailstorm area (123 %), lifetime (72 %), path length (107 %), and maximum reflectivity (6 %). A rise in total annual storm area, hail area, and hail pulse counts throughout the storm's lifetime was contrasted by a decline in daily storm counts, indicating increasing hailstorm organisation. Our findings generally align with expectations of convective intensification. However, some technical data uncertainties remain and large variability necessitates further research.

The effect of 3 °C global warming on hail in Europe

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Hail is a severe weather phenomenon in the Alpine region causing extensive damage to life and infrastructure. However, it is still unclear how hail events change in a future warmer climate. In the scClim project, we conducted convection-permitting regional climate simulations over Europe using the model COSMO with a ~ 2.2 km horizontal resolution. The simulations encompass both present-day climate conditions for 2011 – 2021 and a climate scenario with a 3 °C global warming using a pseudo-global-warming approach. ERA5 reanalyses were used as boundary conditions and a CMIP6 simulation (MPI-ESM1-2-HR) for the large-scale climate-change signal. The simulations, with integrated online diagnostics for hail and lighting, provide total precipitation and maximum hail size estimates every 5 minutes, together with the maximum hourly lightning potential. This detailed model output allows for hail cell tracking in the climate simulations and the analysis of hail events in a warmer climate. The present-day simulation has been validated against observations of temperature, precipitation, hail and lightning. For hail in particular, the model validation with radar-based, station-based and crowd-sourced observations shows an overall good model performance in simulating hail on spatial, diurnal and seasonal scales. This allows further study of the climate signal of hail as simulated with the pseudo-global-warming approach. We plan to show first results of the simulation with a 3 °C global warming, namely, the changes in the spatial distribution and seasonal cycle of hail in Europe as well as the lifetime, storm area and location of hail cells.

Exploring future hailstorms and convective storm features across Europe using km-scale simulations

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The response of severe convective weather to the changing climate remains highly uncertain. With increasing computational capabilities, climate model resolutions have reached those of weather forecasting models, and decade-long pan-continental simulations permitting convection have now become possible.

The Met Office Hadley Centre ran two decade-long simulations covering Europe, for the current climate and an end-of-century RCP8.5 (high emissions) climate, with 2.2 km grid. We explore these simulations to assess future changes in hailstorms across the continent, with a novel severe hail proxy that represents the likelihood of hail >2cm at the surface. The proxy utilizes outputs available from convection permitting models, and simulates the current climatology of severe hail in Europe reasonably well. Results suggest a general decrease of severe hail in the future, despite increases in instability and convective storms. However, very large hail frequency increases especially in Southern Europe. We identify a warmer set of thunderstorms, distinct from current ones especially in the autumn, and around Mediterranean coasts. Apart from hail aspects, we analyze the findings of extremely unstable environments in the future simulation, and thunderstorm properties embedded in such environments, Illustrating using an example of a future extreme episode.

Radar and environment-based hail damage estimates using machine learning

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Infrequent yet impactful, large hail events can swiftly induce significant economic losses within minutes of occurrence, necessitating accurate observation and comprehension of these phenomena to enhance mitigation strategies. While in-situ observations offer precision, their limited occurrence per storm restricts their utility. Weather radars, however, provide broader coverage but face challenges in accurately estimating hail size due to factors like horizontal advection of hailstones, diverse hail size distributions, complex scattering and attenuation, and the presence of mixed hydrometeor types.

This study introduces a novel radar-derived hail product, developed by using a large dataset of hail damage insurance claims and radar observations. Coupled with environmental data, a Hail Damage Estimate (HDE) is computed using a deep neural network approach, achieving a critical success index of 0.88 and an observed damage coefficient of determination of 0.79. Furthermore, the HDE is compared with MESH, a prevalent hail size product, revealing meteorological conditions associated with biases in MESH estimates.

Environments characterized by low specific humidity, high CAPE and CIN, gentle upper-level winds, and southerly surface winds are associated with a negative MESH bias, possibly attributed to variations in hail size distributions, hail hardness, or mixed hydrometeor types. Conversely, environments with low CAPE, high CIN, and elevated specific humidity aloft are associated with a positive MESH bias. This comparative analysis sheds light on biases in existing hail size estimation methods and their potential underlying meteorological factors.

Forensic post-storm investigations of hailstorms and their impacts

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There remain important gaps in our understanding of the finer details of how hailstorms generate damage. While on-site damage documentation of impacts resulting from other hazards such as extreme winds and earthquakes are quite common, particularly from an engineering perspective, such detailed forensic investigations of hail impacts remain rare internationally. Since 2022, the Northern Hail Project has conducted over 10 forensic investigations in multiple jurisdictions and geographical areas across Canada. Insights from these investigations include hailstorm characteristics (e.g. hailfall density, size distribution, maximum size) as well as detailed information on damage to impact receivers (e.g. damage to building surfaces, crops, trees and vehicles, human and livestock casualties). These investigations provide immeasurable opportunities for significantly improving our understanding hailstorm (and hailstone) characteristics, as well as the real-world performance of building materials. This information will be used to improve all aspects of hailstorm science, from hailstorm forecasting and nowcasting through ground-truthing of storm characteristics, as well as connecting those characteristics to the resulting impacts. The latter is being used to develop and improve the quantification of impact thresholds (i.e., how and why hailstorms generate varying levels of damage) as well as in the development of adaptation response measures for hail, such as clearly indicating which building materials perform best under severe hail loading. In addition to this work, the survey team has documented especially severe damage resulting from so-called “wind-driven” hail events, or “WHEs”. When combined with hail, strong winds not only increase the impact energy (i.e., damage potential) of the hail, but the resultant change in impact angle of wind-driven hail also begins to affect surfaces that would typically be protected from the hail. Preliminary findings from these investigations, as well as upcoming improvements and collaborative work with international partners, will be presented.

Sub-severe hail: The missing piece in assessing property risk in North America

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Hail risk is a growing problem for homeowners and insurers, costing the insurance industry billions of dollars each year in the United States. Insurance claims analysis has shown, far more asphalt shingle roof claims are occurring at maximum hail sizes previously thought to not affect most roofing materials. Research conducted by The Insurance institute for Business and Home Safety (IBHS) and ZestyAI demonstrates the need for more attention and consideration to be made in terms of the risk sub-severe hailstones have on roof cover damage. Research shows sub-severe hailstones fall much more frequently than large hailstones leading us to believe their cumulative damage is much higher than previously expected. Claims verification processes tend to focus on very intense hail events. Insurance carriers primarily consider damage from stones two inches and greater as part of their risk solutions, disregarding the majority of hailstorms, as more than 95 % do not contain large hailstones. IBHS applied observations of these types of hail events to guide laboratory testing of asphalt shingles to these conditions. Experiments show high concentrations of small hailstones can reduce a roof's lifespan, make the roof cover more susceptible to damage from future hail events and exacerbate the natural aging of asphalt shingles. ZestyAI accounted for these damage modes with a "Predictive Susceptibility" approach which can lead to more profitable underwriting, a greater ability to rate previously avoided areas, and significantly reduce loss-ratios.

Modeling crop hail damage footprints with single-polarization radar

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Hail is a major threat to agriculture in Switzerland and beyond and assessments of current and future hail risk are of paramount importance for decision-making in the insurance industry and the agricultural sector. Hail climatologies have been developed in recent years. However, inferring crop-specific damages from observational information on hail remains challenging. Here, we build and systematically assess a model to predict hail damage footprints at different spatial resolutions for field crops (wheat, maize, barley, rapeseed) and grapevine from the operational radar product Maximum Expected Severe Hail Size (MESHS). Radar information is combined with a detailed agricultural land-use database and geo-referenced damage reports from a crop insurer for 12 recent hail events in Switzerland. We first show that the model skill is best at 8 km spatial resolution for field crops but at 1 km for grapevine, which is attributed to the different spatial distribution of the two crops. For the lowest possible MESHS threshold (20 mm) the model has a high probability of detection (80 %) but predicts damage about two times too often. Adjusting the threshold to 30 – 40 mm balances the frequency bias, nearing an optimal value of 1, though with a reduced probability of detection (around 50 %). Hence, the choice of the threshold depends on user needs and the costs associated with false alarms or missed events. Considering only areas with high cropland density substantially reduces false alarms.

We integrate this framework into the open-source modeling platform CLIMADA and use it to build a hail damage footprint climatology for different crops during their growing period and particularly vulnerable phases over the past 20 years. Thus, we provide a flexible, open-source framework to assess agricultural damages after a hailstorm and present climatological information on hail damages tailored to specific crops.

Hail diameter footprints and simulations of hail damages

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Damages occurring from hailstorms have measurably increased in the last years, mainly caused by higher exposure and increased vulnerability but also partially caused by anthropogenic climate change. Further increases in damages in the next years are expected and the understanding of hail risks becomes more and more important for society, companies and insurers.

For better understanding hail risks, we develop a stochastic hail risk model, which generates a large synthetic event set of realistic hail events. In combination with exposure and vulnerabilities, actual damages can be simulated. One challenge for developing such a synthetic event set is the need for realistic hail footprints with spatial patterns of maximum hail sizes based on historic events. Radar observations do not provide sufficient information about hail diameters and ground-based hail reports do not provide representative information or sufficient coverage. Instead, we use detailed loss and exposure information from an insurance portfolio which is available on coordinate level. We aggregate this information spatially to obtain spatial patterns of loss behavior, such as affected ratios or damage ratios. A machine learning algorithm is then trained based on ground-based hail reports to transform the loss patterns into actual hail patterns.

The resulting footprints have already proven useful for evaluating other radar-based hail products and will allow for a location-based risk assessment of hail damages within the synthetic event set.

Seamless coupling of kilometer-resolution weather predictions and climate simulations with hail impact assessments for multiple sectors (scClim)

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Hail is a significant contributor to weather-related damages in Switzerland, driving a demand for actionable information on hail risks across sectors in current and future climate. The ongoing research project scClim (https://scclim.ethz.ch/) addresses this demand, uniting complementary expertise to establish a seamless model chain from observing and modeling the weather and climate to the quantification of hail impacts on agriculture, buildings, and cars. In this talk, an overview of the interdisciplinary research project is provided. The project is structured into five strongly interconnected subprojects. Subproject A engages in a close dialogue with key stakeholders to co-design a hail impact assessment platform, incorporating outcomes from the other subproject for practical applications. Subproject B develops an algorithm to track hail cells and applies it to operational weather forecasts and climate simulations to investigate hail cell characteristics. The kilometer-scale convection-permitting climate simulations over Europe are conducted with the regional model COSMO, with the HAILCAST hail growth model embedded. These simulations provide case studies and a 10-year climatology of present-day conditions and a 3 °C global warming scenario using a pseudo-global-warming approach. Subproject C generates a multi-decadal time series of past hailday occurrences in the Swiss radar domain to identify the drivers of inter-annual hail variability and changes in hail seasonality. Additionally, it explores the potential of polarimetric data from the Swiss weather radar network to provide information about the probability and size of hail on the ground. Subprojects D and E construct hail damage models for crops, buildings, and cars to extend the open-source impact modeling platform CLIMADA. The applied vulnerability curves are calibrated with damage data from 2002 to 2021, which was obtained from insurance companies. Ultimately, the developed framework is used to assess the implications of climate change for future hail risks in the addressed sectors.

New hail hazard map for Austria

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Severe hail can have devastating consequences for people, the environment and the economy. Better knowledge of the distribution, frequency and extreme characteristics of hail events improves our understanding of the phenomenon, predictions of its occurrence and, as a consequence, the development of effective measures to mitigate damages. New hail hazard maps were developed for Austria based on fourteen years of three-dimensional radar data (2009 – 2022). A comprehensive dataset of hail reports from eye-witnesses and fire brigade units was used to calibrate the hail size indicator MEHS (maximum estimated hail size, Witt et al., 1998) to recorded hailstone sizes. The calibrated hail size archive, derived from radar data, was then used to assess frequencies above certain thresholds as well as maximum observed hail sizes in Austria. The method used for the calculation of the return levels is a version of the meta-statistical extreme value distribution (MEVD). A max-pooling approach was employed to enrich the dataset and to reduce remaining artefacts. A distributional assumption about the frequency of the estimated hail sizes from radar data was retrieved and the parameters of the distribution (Weibull) were then modeled via a Neural Network, which takes topographic and temporal information of the hail size values as well as additional atmospheric covariables as input information. The result was a spatio-temporal model across Austria, from which the return levels were extracted. The newly developed hail hazard maps provide comprehensive insight into observed hail events in Austria but also an estimation of return levels. Shortcomings of radar measurements for hail detection are examined in supplementary quality maps.

Spaceborne remote sensing of hail: Retrievals, climatologies, and challenges going forward

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In addition to the myriad threats that severe hailstorms pose to society, infrastructure and agriculture, severe hail is difficult to measure in situ, and surface-based hail reporting and detection methods are inconsistent and subject to geographical or societal biases. This motivates the use of spaceborne remote-sensing platforms to retrieve hail and construct climatologies in the most globally consistent way. Passive-microwave algorithms leverage the sensitivity of spaceborne passive-microwave radiometers to scattering by hail, particularly in the channels from 10 to 89 GHz. These retrievals are used to construct global climatologies of severe hail. The Bang and Cecil (2019) retrievals has been applied to several different spaceborne sensors: the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), Global Precipitation Measurement Mission (GPM) Microwave Imager, Advanced Microwave Scanning Radiometer for EOS (AMSR-E), and Advanced Microwave Scanning Radiometer 2 (AMSR2) sensors and used to construct [near] global climatologies of severe hail. This retrieval, and others, have been tested using Global Precipitation Measurement (GPM) Ku-band precipitation radar, to assess their effectiveness and regional variability. A successful retrieval and climatology are those that correspond tightly to radar reflectivity and give minimal appearance of regional biases, especially with latitude. Satellite platforms offer consistent observations, even in remote, data-sparse, and oceanic regions that ground-based networks exclude. There are, however, potential disconnects between the processes identified aloft by the satellite and the resultant weather at the ground, leading to uncertainties in the retrievals that may propagate into satellite-based climatologies, particularly in the Tropics, where there are abundant strong - but not necessarily hailing - storms that are strongly represented in the current satellite climatologies. There are ongoing efforts to assess and mitigate the contributing factors to these uncertainties, chiefly among them the effects of non-uniform beam filling in the passive-microwave footprint, and the relationships between the size distributions of hailstones aloft and the dynamic processes and environments with which they interact throughout their trajectories.

Environment and convective mode of severe hail-producing storms in the United Kingdom

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Costly impacts from severe hail events in northwest and northern Europe are currently rare compared to central Europe, but convective environments in these ‘peripheral’ countries deserve closer investigation as risk may increase in future. Recent studies seek a ‘recipe’ of local convective parameters that can statistically predict the occurrence of severe hail globally, although the most relevant parameters are known to vary regionally. Pan-European studies are, in practice, biased towards central Europe where reporting rates to the European Severe Weather Database have historically been highest. The UK, with its strongly maritime, temperate climate, is an example of a peripheral country. Is the severe hail ‘recipe’ the same or different to (i) central Europe (ii) a swath of peripheral countries?

Using a combined database of UK severe hail events – radar-verified since 2004 – and a large set of convective parameters from ERA5 reanalysis, we analyze the environments producing severe hail in the UK. Initial results indicate that UK severe hail environments fall generally within the pan-European parameter space, but very large hail may occur with stronger deep layer shear and lower CAPE. We previously found that most very large hail in the UK is caused by supercells. We also corroborate findings from the literature that low level shear does not discriminate between marginally large and very large hail. Future work will use logistic regression models to determine the optimal recipe of parameters for the UK.

In summary, the basic ingredients of severe hail appear consistent with central and pan-European studies but the optimal local conditions for high-impact events appear slightly shifted in the maritime climate of the UK. Adding this variability into statistical models of convective hazards derived primarily from severe hail hotspots should enable better current and future assessments of hail risk.

Hail in Switzerland – Modeled trends, decadal variability, and large-scale drivers

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There is still the need for a better understanding of what drives the inter- and intra-annual variability of hailstorms in Switzerland. We currently lack long-term, consistent information about the occurrence of Swiss hailstorms. To address this gap, we developed statistical models that reconstruct past hail days in the Swiss radar domain from 1959 to 2022 from environmental information from ERA5 trained on radar-based hail observations. Two regions north and south of the Alps are analyzed separately. The time series show a strong significant positive trend in yearly haildays in both the southern and northern domain, driven mainly by increased atmospheric instability and moisture in ERA5 in recent decades. We also see an increase in hail days at the beginning of the convective season but no systematic changes in the seasonal cycle over the last six decades. There is substantial natural variability in both regions. We investigate the large-scale mechanisms that influence this variability and the seasonal cycle of Swiss hail activity through analyzing synoptic composites, distinguishing between months and seasons with few and many hail days. Potential drivers and precursors include soil moisture conditions, sea surface temperature anomalies, large-scale variability patterns (Piper and Kunz, 2017), central European weather types (e.g. Rohrer et al., 2018), and cold fronts (Schemm et al., 2015, 2016). Together the results of this study shed new light on long-term trends, decadal variability and it's drivers of Swiss hailstorms.

Radar-based hail damage modelling for buildings and cars in Switzerland: Model evaluation and ways forward

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Hailstorms cause significant damage to buildings and cars in regions with frequent severe thunderstorms. In this study, we develop and evaluate an open-source model that can provide real-time hail damage assessments for buildings and cars using radar-based hail proxies in Switzerland. Of the analyzed hail proxies, the Maximum Expected Severe Hail Size (MESHS) performs best and provides damage estimates with the correct order of magnitude for most medium-impact and all high-impact events in the period from 2002 to 2021. However, large uncertainties remain in the spatial structure of hail swaths, as MESHS does not consistently distinguish between areas with small and severe hail. As a result, areas with extreme MESHS of over 60 mm cause building damages in less than 50 % of all cases, despite the presence of exposed buildings and explicit consideration of wind-driven hail drift. This uncertainty may be reduced in the future by including radar-based hail proxies based on dual-polarization radars or alternative data sources. For example, a case study of a recent severe hailstorm on 28 June 2021, reveals the large potential of crowdsourced data to improve real-time damage estimates in densely populated areas. Furthermore, work in progress aims to expand the hail damage model to use high-resolution convection resolving simulations calculated with the numerical weather forecast model COSMO and the hail growth module HAILCAST as input. With available 2 km nested climate simulations applying the pseudo global warming approach, our damage model will allow for a hail risk assessment under climate change.

Practical use of hail climatology in crop insurance

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We used MeteoSwiss hail climatology to develop a risk model for hail in Switzerland. At the spatial resolution of 1 km^2 we calculated the risk hail risk premium for the main broadacre crops, wine grapes, fruits and grassland.

The hail risk premium can be calculated by considering the frequency of a hail event as well as the severity (impact) of the hail damage to the crops. Whereas most often the hail risk premium is calculated based on historical losses / burn costs, we developed a stochastic modeling framework.

The hail climatology serves to calculate a frequency distribution of hail days. Swiss Hail's own loss data base allowed us the calculate the distribution of damage degrees (severity) for every crop type in scope. The missing link between hail frequency and loss severity is a transfer function describing the percentage of the hail policies that is affected in case a hailstorm passes by. This transfer function takes account for the discrepancy between hail observations derived from radar measurements and potentially damaging hailstones that reach the ground. The output of the model is a loss frequency curve to which specific features of the insurance policy (like limits or deductibles) can be applied before calculating the risk premium. In case a proper hail climatology is missing, it can be approximated by lightning data or parameters describing atmospheric instability.

A new global model framework for representing weather systems responsible for observed hail occurrence over the US and Europe

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As a developer of catastrophe risk models, Verisk is investing in new approaches to modeling atmospheric perils associated with severe thunderstorms including hail. To this end we are in the process of developing a capacity to make use of a new Global Model framework for simulating the development of severe weather environments at 30 km resolution. The presentation will focus on progress we have made to estimate the probability of hail occurrence within the US using environmental predictors. Over the next year we will adapt and test this approach for Europe. The Global Modeling framework will then allow us to construct millions of severe weather hail events over Europe. The Global Model framework makes use of a 2500-member ensemble of historical weather events over the past 40 years that is generated using the standard 1-degree configuration of the Community Atmosphere Model (version 4) using the AMIP experiment design. The unprecedented 100'000-year size of this ensemble allows us to determine, much more clearly and without statistical extrapolation, the forcings and processes that generate weather extremes in the tail probability of their occurrence. However, the potential value of this dataset for natural catastrophe modeling is undermined by deficiencies in CAM4 to replicate the location, frequency, and intensity of observed storms. To this end, Verisk Research and collaborators within academia have developed a novel Deep-Learning algorithm trained on ERA5 data and higher resolution datasets of historical weather events to debias and downscale 3-hourly CAM4 output. With the ability to infer hail occurrence from these weather states, we will be able to estimate the return period of observed events like the events that affected France in 2022 and Italy in 2023.

Comparison of ML models to create hail risk in the Contiguous United States

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Among the severe convective storm perils, localized hail events cause widespread agricultural and property damage. In recent years, the annual financial losses due to hail have consistently exceeded $ 20 billion, therefore accurately capturing the hail climatology is a crucial ingredient for any severe convective catastrophe model.

In this presentation, we present 40-year annual climatologies of hail in the contiguous United States. We used three different machine-learning (ML) methods to establish a link between observed hail events and convective parameters calculated from reanalysis (ERA5) to model spatial patterns of daily hail risk in the contiguous U.S. The three ML methods are: a generalized linear model (GLM), a random forest model (RFM), and a Gradient Boosting Tree model. We trained these models with Storm Prediction Center (SPC) hail observations and the reanalysis-based convective parameters. On top of parameters describing instability, moisture, and wind shear, we offer several parameters to the models which are linked to dynamic lifting including Q-vector convergence, low level moisture convergence, and thermal front parameter. We compare, and contrast these models, and discuss trends in the modeled hail probabilities over the last 40 years. All three methods led to very similar results, supporting the hypothesis that the selection of convective parameters is more important than the selection of the ML method itself.

A comprehensive review of recent catastrophic hail events and their impacts on the insurance industry

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In the last couple of years, the insurance industry has faced challenges due to increase economic losses from catastrophic hail events. Series of severe storms in 2022 and 2023 across Europe have caused unprecedented industry losses in some countries. In this study, we are reviewing select recent major hail events across Europe using the Verisk Severe Thunderstorm Model and provide a roadmap for the insurance industry to navigate the challenges posed by catastrophic hail events. The focus will be on benchmarking the hazard and loss outputs generated by our model against the observed events. The model accounts for the real-world behavior of severe thunderstorms, allowing users to assess their exposures from the local scale to the macro level. The model leverages multiple data sources to realistically capture the risk from hail and straight-line wind in a unique hybrid physical statistical approach that helps better quantify insured risk.

Considering climate change and natural climate variability when comparing stochastic hail loss model output against recent loss history

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The purpose of a stochastic natural catastrophe hail loss model as used in insurance and reinsurance is to represent the full range of possible sequences of hail events in both spatial and temporal dimension under current climatic conditions. When comparing a model against recent history, it must be recognized that the historical event sequence represents only one possible realization of the sample space. Furthermore, past monetary losses of hail events must be corrected to account for inflation and changes in the building and auto stock, but also changes in the climatic conditions.

Based on ECMWF ERA5 reanalysis, we attempt to assess the natural climate variability of severe storm frequency in Europe and to detect temporal trends. The goal is on one hand to inform whether the past decade of hail loss experience in Europe was exceptional from a natural climate variability point of view, and if loss adjustments need to be made to earlier events to account for transient climate change.

Leveraging machine learning and AI in hail prediction and forecasting

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Predicting the occurrence of hail is an ongoing challenge, both in terms of expected size and coverage at a range of timescales, from multiday periods to next-hour. Given yet another season of record hail events in 2023 globally, this naturally raises the questions of how we address this predictive limitation and what tools may be available for providing information to mitigate hail impacts. Hail predictions have traditionally explored a variety of timescales through both modeling and statistical approaches, though relatively few skillful predictors or predictive methods have been identified using these methods. However, these efforts have been in part hampered by a failure to focus on the underlying quality-control of the training data, including not considering the representativeness of hail size observations, inappropriate use of nulls, and a reluctance to look beyond existing parameters or frameworks. Adding to this challenge, recent work has highlighted a stochastic and non-linear characteristic to hail growth that shows multiple pathways and processes that can produce large hail, suggesting that techniques which incorporate this property are necessary. This lends itself to an emerging set of artificial intelligence and machine learning techniques, that range from unsupervised, to semi-supervised, and to deep learning approaches. These techniques employed with new datasets including long-duration radar data from the GridRAD archive, satellite-based storm characteristics, and quality-controlled hail observational datasets, signpost a new frontier in hail prediction. This presentation will focus on combinations of these rich datasets with hierarchical modeling predictive strategies and deep learning to provide new insights into how we can improve hail prediction in the next-hour, through to the outer limits of predictability.

Drone-based photogrammetry combined with deep-learning to estimate hail size distributions and melting of hail on the ground

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Hail is a major threat associated with severe thunderstorms and estimating the hail size is important for issuing warnings to the public. For the validation of existing, operational, radar-derived hail estimates, ground-based observations are necessary. Automatic hail sensors, as for example within the Swiss hail network, record the kinetic energy of hailstones to estimate the hail sizes. Due to the small size of the observational area of these sensors ($0.2\,m^2$), the full hail size distribution (HSD) cannot be retrieved. To address this issue, we apply a state-of-the-art custom trained deep-learning object detection model to drone-based aerial photogrammetric data to identify hailstones and estimate the HSD. We present the results of a single hail event on 20 June 2021. The survey area suitable for hail detection within the created 2D orthomosaic model is $750\,m^2$. The final HSD, composed of 18'209 hailstones, is compared with nearby automatic hail sensor observations, the operational weather radar based hail product MESHS (Maximum Expected Severe Hail Size) and crowdsourced hail reports. Based on the retrieved data set, a statistical assessment of sampling errors of hail sensors is carried out and five repetitions of the drone-based photogrammetry mission within 18.65 min after the hail fall give the opportunity to investigate the hail melting process on the ground. Finally, we give an outlook to future plans and possible improvements of drone-based hail photogrammetry.

Double moment normalization of the number distributions of hail size over Switzerland

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Since June 2018, the Swiss automatic hail sensor network has collected estimates of hail diameters in three regions: Ticino, Napf, and Jura. We propose the use of double moment normalization for modeling the hail size number distribution (HSND), which is defined, for each diameter, as the number of hailstone impacts measured by one instrument during an event. The HSND is dependent on the detection area of the sensor and the duration of the event. Using two of the empirical moments of the HSND, we compute a normalized distribution, which is shown to have limited variability across all the events taking place in the three geographical regions of deployment of the sensors. Thanks to its invariance in space, a generalized gamma can be used to model the normalized distribution, and its parameters have been determined through a fit over approximately 70 % of the events. The fitted model and the previously chosen pair of empirical moments can be used to reconstruct the HSND at any location in Switzerland. The accuracy of the reconstruction has been estimated over the remaining 30 % of the dataset. An additional evaluation has been performed on an independent HSND, made of estimates of hail diameters measured by drone photogrammetry during a single event. This HSND has a much larger number of hailstone impacts (18’000) than those of the hail sensor events (from 30 to 400). However, we found that the fitted generalized gamma model obtained from the sensor data can reproduce well the HSND recorded by the drone, highlighting the invariance of the normalized distribution and the adaptability of the method to different data sources.

Improving our understanding of hail hazards using machine learning

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Hail storms can cause tremendous damage to vehicles, buildings, and agriculture and are responsible for as much losses as hurricane in the United States, about 10 billion US dollars per year (Pielke et al., 2008; Tang et al., 2019). Hail occurs in very specific environmental conditions featuring substantial amounts of buoyancy and vertical wind shear. Damaging hail can be produced by different convective storms such as pulse storms, multicells, and mesoscale convective systems but the largest hail stones are typically produced by supercells.

In this study, we analyze large-scale environmental conditions to estimate damaging hail hazards on a global scale. We use the algorithm presented by Prein and Holland (2018) on hourly ERA5 reanalysis data (31 km $\times$ 31 km grid cells) over the period 1959 – 2022. The algorithm's hail predictions agree well with observed hail reports in the US, Europe, and Australia especially in regions with strong orographic forcing. The algorithm accurately predicts large hail frequencies globally and adequately represents the annual cycle of hail in most regions. The longer data record also enables trend analysis, the understanding of inter-annual variability and the impact of teleconnections such as El Niño on large hailstones.

Additionally, we test the XGBoost gradient-boosting machine learning method to investigate if our results based on the Prein and Holland (2018) algorithm can be improved by a purely data-driven approach. XGBoost is an ensemble learning technique that combines the predictions of multiple decision trees to create a stronger, more accurate model. The main advantages of using such a machine learning method are that it captures non-linear relationships between predictor variables, handles missing data, and benefits from ensemble learning. This approach will also enable us to assess hail hazards for hailstones larger than 2.5 cm in diameter, which we used for the initial analysis. We will present the evaluation results of both approaches, global maps of damaging hail hazards including long-term trend and variability assessments, and summarize the strengths and weaknesses of each approach including future research needs.

Observations of hailstone-like trajectories and growth

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The recently developed Hailsondes provide new observations of hailstone-like trajectories and growth conditions within convective storms. This new instrument was deployed in 2023 as part of the Large Hail Formation and Trajectories (LIFT) project in southwest Germany and the Northern Hail Project (NHP) in Alberta, Canada. On 24th July, successful observations were obtained during the Northern Hail Project of training supercells which produced a tornado and hail exceeding 85 mm in maximum dimension. Two hailsondes were launched five minutes apart, both measuring updraft speeds of more than 37 ms^{-1} during balloon-assisted ascent and continued to ascend after balloons separation to over 5000 m AGL. Despite traveling along similar trajectories, the first sonde experienced wet growth conditions and significant icing, while the second sonde experienced dry growth conditions and less icing. Investigation of ECCC polarimetric weather radar data shows subtle changes in the hailsonde pathway relative to the bounded weak echo region and KDP column likely explains the differences in icing conditions. Our presentation will provide an overview of the latest hailsonde hardware design, initial field campaign results, comparison to 3D wind simulations, and planned future activities.

Unravelling the mysteries of hail

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The escalating damage costs associated with hailstorms have resulted in a renaissance in hail research in recent years. In Canada, coordinated hail research is once again being undertaken following an almost 40-year hiatus since the Alberta Hail Project was dissolved in 1985 the Northern Hail Project (NHP) was formed in early 2022. We have now completed two successful field seasons in Hail Alley (Alberta, Canada). This has been a valuable learning experience on how to conduct field research targeting hailstorms, and many valuable lessons have been learned. The field research has also seen the deployment of Canada's first urban hail monitoring network in Calgary, collection of over 3000 hailstones, 3D scanning of hailstones, and the development of an automated machine vision technique to objectively analyze hailpads. Several innovative instruments have also been deployed, including motion-activated cameras that share data in real time over the mobile network, and a miniature, continuous waveform radar for measuring the fall speed of natural hailstones. We have also been collaborating with international partners. For example, in July 2023, we aided the Bureau of Meteorology (Australia) in the first successful deployment of a hailsonde in a supercell hailstorm. Last, but not least, we have undertaken over a dozen forensic level hail damage surveys over cropped land and urban areas. In addition to sharing our experiences and lessons learned, we will highlight some preliminary results and outline future plans. The NHP is not only an exciting opportunity to undertake ground-breaking research in Canada, but also an opportunity to school a new generation of scientists specializing in severe convective storms.

Enhancing insights into large hail formation and trajectories through targeted field campaigns

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Current methods for radar-based nowcasting of hailstorms assume that the expected further evolution of observed hail is primarily governed by advection; they do not consider ongoing hail growth and production. Combined with the complex internal structure and dynamics of hailstorms, large uncertainties result in the forecasted hail size distribution and area impacted by hail at the ground. The goal of the project "Large Hail Formation and Trajectories (LIFT)" is to advance current schemes towards a physically-based nowcasting of hail in order to generate an observational basis for and derive a first radar-derived hail growth and nowcasting scheme. Indicators of hail production and growth will be identified through the combined evaluation of observation and simulation datasets that will form the basis of an observationally-based hail growth model. LIFT started in summer 2023 with a field campaign in southwestern Germany aligned to the Swabian MOSES field campaign, which focused on the event chain of hydro-meteorological extreme. MOSES includes highly flexible and mobile observing modules (such as the KITcube) specifically designed to study the interactions of short-term events and long-term trends across all Earth compartments. The study area of Southwest Germany was chosen because it represents the major hot spot for severe hailstorms in Germany. Our presentation gives a brief overview of the LIFT and Swabian MOSES 2023 field campaigns, showcasing key observations from selected Intensive Observation Periods (IOPs) featuring hail occurrences. Utilizing small and lightweight radiosondes launched with helium-filled balloons, we traced the trajectory of hailstones through the updrafts of hailstorms. Our analyses reveal a sequence of cyclonically/anticyclonically curved trajectories upon entering the updraft, with no observed instances of repeated up/down vertical excursions. These direct observations, when integrated with radar data, offer insights into potential hail growth mechanisms.

The IBHS field research program: Over a decade of observing hail and hailstorms

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The Insurance Institute for Business & Home Safety's (IBHS) multifaceted hail research program was developed in 2011 with two pillars. The first, evaluate and improve upon laboratory hail impact testing standards. The second, develop a field research program to fill in existing scientific gaps to enable the first pillar to be accomplished. The first IBHS hail field experiment occurred in 2012, with the objective of proving that hail strength testing could be conducted in the field and help fill a gap in understanding the material properties of hailstones. Since 2012, the program has produced a collection of hailstone measurements that now exceed 4,500 hailstones and represents the largest research-grade hailstone database in the world. The program has also evolved to move beyond hailstone measurements but pioneered the use of 3D laser scanning technology to create detailed digital models of hailstones. These data, through research partnerships, have been used to increase our understanding of the radar back scattering properties of natural hail shapes, improve estimates of hailstone aerodynamic properties, and open new avenues to parameterize hailstones within numerical weather prediction models. The program also developed a fleet of rapidly deployable impact disdrometers which have been used to map hailswaths and understand variability in hail size distributions and concentration at the ground from hailstorms as well as to guide novel laboratory experiments. This presentation will provide an overview of the program and its contributions to hail science and opportunities for furthering the reach of the data collected from the program.

Going inside of hailstones from a giant hail event in Catalonia

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On August 30, 2022, a massive hailstorm struck the northeastern part of Catalonia, resulting in the most severe episode ever documented in the region. Hailstones exceeded 10 cm in size in La Bisbal d'Empordà, a small town with 10'000 inhabitants, and its surrounding areas. In many other locations, hailstones measured more than 5 cm. Considering only the damages in La Bisbal d'Empordà village, it exceeded 6 million euros, with over 200 people injured, and sadly, a two year old child lost her life. Through intensive fieldwork and the help of various spotters, researchers collected some of these hailstones for analysis. The first step was a chemical analysis conducted in the laboratory, which revealed a clear connection between the main components and their proximity to the sea. One of the causes of this phenomenon was attributed to the influence of low level winds blowing from the southeast, transporting humidity into the thunderstorm. Additionally, we have used tomography (CT scanning) to examine the internal structure of the hailstones in three dimensions. This allowed us to observe the diverse layers within the hailstones and their varying densities. This analysis provided valuable insights into the processes that these stones undergo within thunderstorms, influenced by temperature and humidity in different atmospheric layers.

Current status of SINFONY – The combination of nowcasting and numerical weather prediction on the convective scale at DWD

Ulrich Blahak[1] and the SINFONY Team

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The development of DWD's new Seamless Integrated Forecasting system (SINFONY) for Germany has matured, and a number of its components has been run continuously during the last three convective seasons. This presentation will give a short overview on the system components, their status and results of last years season. There are different öptimalfforecast methods for different forecast lead times and different weather phenomena. Focusing on convective events and their related hazards up to some hours ahead, we developed a) radar Nowcasting ensembles for areal precipitation, reflectivity (STEPS-DWD) and convective cell objects including hail and life cycle information (KONRAD3D-EPS), b) regional ICON-ensemble model (ICON-RUC-EPS) with assimilation of high-resolution remote sensing data (3D radar volumes, Meteosat VIS and IR channels, lightning, cell objects) and hourly new forecasts on the km-scale, c) optimal combinations 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". d) systems for common Nowcasting and NWP verification of precipitation, reflectivity and cell objects. For b), efficient forward operators for radar volumes and visible/infrared satellite data (SEVIRI-VIS/IR) 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 c), the ICON-RUC-EPS outputs simulated reflectivity volume scan 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 (a) and NWP (b).

Integrating KONRAD3D into the nowcasting guidance system NowCastMIX at DWD

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Short-term warnings for severe thunderstorms are generated at the German Weather Service (DWD) through the NowCastMIX system, providing automated warnings for the next 60 minutes. NowCastMIX processes meteorological fields from various sources, including NWP, radar, surface station reports, and lightning detections. Every 5 minutes, the system employs a hierarchy of fuzzy logic sets to calculate the potential for heavy rain, hail, and severe gusts based on available data. Categorical thunderstorm warnings are then issued for detected cells, and regions requiring warnings are identified by condensing the information into clusters. NowCastMIX previously relied on the KONRAD and CellMOS cell detection schemes, which both utilized two-dimensional radar scans for automatic detection, tracking, and prediction of thunderstorm cells. In recent advancements, KONRAD and CellMOS schemes within NowCastMIX have been replaced by KONRAD3D. This novel scheme introduces new state-of-the-art approaches, providing three-dimensional objects of detected cells through 3D radar volume scans. Importantly, KONRAD3D utilizes the output of the hydrometeor classification algorithm HYMEC for its hail flag calculation. This advanced approach goes beyond the previous rudimentary KONRAD calculation of looking for high dBZ values at the precipitation scan and contributes to a better hail estimation within the fuzzy logic of NowCastMIX. To ensure a smooth transition in the warning strategy, it is crucial that the shift from KONRAD and CellMOS schemes in NowCastMIX to KONRAD3D is seamless, minimizing significant changes in the issued warnings. Consequently, the fuzzy logic within NowCastMIX has been meticulously fine-tuned during the reanalysis phase based on 194 convective days over three convective seasons. The objective was to maintain consistency by generating a similar number of severe and extreme warnings as observed with the previous KONRAD and CellMOS schemes. Looking ahead, future work will focus on the implementation of three-dimensional cell features into NowCastMIX that leverage the capabilities of 3D radar scans. This represents a significant advancement over the limitations posed by two-dimensional approaches like KONRAD and CellMOS. By incorporating these innovations, NowCastMIX aims to further enhance its warning capabilities, adapting to the three-dimensional data provided by KONRAD3D for more accurate and comprehensive severe thunderstorm warnings.

Improvements of the object-based nowcasting system TRT for automatic thunderstorm and hail warnings in the Alpine area

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TRT (Thunderstorms Radar Tracking) is the operational real-time thunderstorm nowcasting and warning system of MeteoSwiss. We present and discuss the latest improvements. These include an enhanced computation of cell severity, which now gives a specific additional weight to the radar-based, operational hail parameters POH (Probability Of Hail) and MESHS (Maximum Expected Severe Hail Size) for the real-time hail warnings. The specific warning for heavy precipitation is newly computed by using an independent severity parameter. It combines the precipitation accumulation in the cell's footprint, measured by the volumetric radar network in the last 30 minutes, with the 60 minutes forecast for the same cell computed by the operational NowPrecip/NowPAL nowcasting systems and provides an early warning of the risk of heavy precipitation. The issued fully automatic warning is then triggered by the highest of the two warning levels. ZDR-columns detected within thunderstorm cells also have the potential to improve the nowcast of severe convection and hail. The separately computed grid-based ZDR-column area and maximum height are included in the TRT cell properties as additional real-time severe weather information for the forecasters. Finally, TRT also includes an automatic, operational lightning jump detection module for each identified storm cell with a time resolution of 2.5 minutes, as an additional parameter for severe thunderstorms. The improved algorithm will be integrated into the convection nowcasting and warning systems already in use at MeteoSwiss, such as TRT, NowPrecip, NowPAL, COALITION and INCA. It provides the basis for the fully automated thunderstorm and hail warning chain in Switzerland.

Testing a spaceborne passive-microwave severe hail retrieval over Argentina using ground-based dual-polarization radar

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Passive-microwave hail detection methods rely on the scattering signal produced by large ice hydrometeors. Recently, passive microwave hail retrieval methods have been trained by pairing TMI [Tropical Rainfall Measuring Mission (TRMM) Microwave Imager] data with United States surface hail reports to present a global hail climatology. As expected, Southeastern South America (SESA) stands out as a hotspot for hail occurrence. Our analysis shows some differences with the available ground hail reports in Argentina, as we expect the most frequent hail storms in Mendoza, Cordoba and Misiones, instead there is a clear hotspot in northeastern Argentina. To assess the retrieval with a regional perspective we take a case study approach and focus on polarization corrected temperature precipitation features (PCTFs) with a detected Phail $>50\,\%$. We mainly rely on polarimetric weather radars and a hydrometeor identification algorithm (HID) as a proxy for ground truth. Results indicate that the hail retrieval is mainly responding to low 37 GHz polarized corrected (brightness) temperatures (PCT) and large PCTF area, while HID outputs show that high probabilities of hail also correspond to abundantly suspended graupel. We suspect that the BC19 hotspot area results from large and mature mesoscale convective systems with deep columns of graupel-sized frozen hydrometeors that translate to low 37 GHz PCT values. Finally, we present very simple radiative transfer simulations that show that with a large graupel water path, hail falling on the ground has indistinguishable brightness temperatures.

Investigating hail remote detection accuracy: A comprehensive verification of radar metrics with 150’000 crowdsourced observations over Switzerland

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Hail detection and sizing using radar is a common practice and radar-based algorithms have been developed and operationally deployed in several countries. Switzerland National Weather Service (MeteoSwiss) uses two radar hail metrics: the probability of hail at the ground (POH) to assess the presence of hail, and the maximum expected severe hailstone size (MESHS) to estimate the largest hailstone diameter. Radar-based hail metrics have the advantage of extended spatial coverage and high resolution, however they don’t measure hail directly on the ground. Therefore, they need to be calibrated and further verified with ground-based observations. Switzerland benefits from a large dataset of crowdsourced hail observations gathered through the reporting function of the MeteoSwiss app. Crowdsourced observations can contain wrong reports, both intended (jokes) or unintended (misuse), and have to be filtered before being used. Radar reflectivity is often used to remove reports where the maximum reflectivity is below a usual storm environment. However, this filtering method renders the observations dependent on the same radar signal used to compute hail metrics. Therefore, we test a spatio-temporal clustering method (ST-DBSCAN) based solely on the data to remove implausible reports. We then use the filtered dataset to make an extended verification of POH and MESHS in terms of Probability of Detection (POD), False Alarms Ratio (FAR), Critical Success Index (CSI) and Heidke Skill Score (HSS). We estimate the most skillful POH threshold to predict the presence of hail. We investigate the conditions leading to POH false alarms (radar signal without observation) and misses (observations without radar signal). We assess how good MESHS is compared to POH in discriminating > 2 cm hailstones, and how good MESHS is in estimating the maximum hail size on the ground for thresholds of 3 cm, 4 cm, and 6 cm. We found that POH has a good skill for hail detection with HSS reaching 0.8 (FAR < 0.2), but that MESHS struggles in estimating sizes above 3 cm (FAR > 0.5).

Pre-storm environments and storm-scale properties of the major hailstorms of 2021, 2022 and 2023 in Europe

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The years 2021, 2022, and 2023 were record-breaking in terms of the severe hailstorms in Europe. 24 June 2021 featured the highest number of large hail reports per day (860) in the history of the European Severe Weather Database. In 2022, the insured damage exceeded € 4 billion in France alone while 215 people were injured by hail that year. In 2023, a series of devastating hailstorms across Italy set the new record for the European hail size twice in 5 days, with the maximum hail diameter estimated at 19 cm.

In this work, we study the most severe hailstorms of the three years and their larger-scale environment in relation to the maximum observed hail diameter and hailstorm lifetime. The studied storm-scale properties include storm type/mode and the occurrence of storm mergers. The larger-scale environment is derived from ERA5 reanalysis. We investigate CAPE-shear parameter space, vertical distribution of buoyancy and hodograph properties (shape, longest segment in the hodograph, and storm-relative winds). More than 170 hailstorms have been selected from the three years, spanning maximum hail diameters of 5 to 19 cm and hailstorm lifetimes of 10 to 690 minutes. For each hailstorm, we calculate the storm-relative winds using an observed storm motion.

The hailstorms were typically discrete supercells, their hodographs having a straight shape with the longest segment between 1 and 3 km with storm-relative inflow exceeding 10 m s^{-1}. Hodograph properties and the amount of CAPE had only weak relation to the duration of the hailstorm. Maximum buoyancy in the hail growth zone had the strongest correlation with the observed diameter, even higher than the CAPE-shear product. In some cases, very large hail occurred in marginally favorable environments only after a storm merger occurred. This shows that storm-scale processes (merger, deviant motion of the storm) and interaction with boundaries can be as important as the background environment. We contrast our results with some of the recent publications on the very large hail environments.

Satellite-based quantification of convective updraft characteristics: Application to hail severity

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Recent numerical modeling studies have emphasized the importance of updraft width in the dynamics of deep convective storms and their attendant hazards. In particular, wide updraft cores appear more likely to: host wide, intense tornadoes; promote strong, deep cold pools; and support the generation of large hail. Motivated by our model-based correlations between the mid-tropospheric updraft-core area and its cloud-top imprint, we are pursuing the use of the high-resolution data from the GOES-R series satellites to develop updraft-area estimation techniques that can then be applied toward hazardous-weather prediction and detection. To illustrate, a method using GOES-16 Channel 14 longwave infrared data to quantify "overshooting-top" area (OTA) is explored as one means to identify the convective storms with the highest likelihood of forming significant hail; overshooting-top depth (OTD), which should provide information on updraft intensity, is another means. Calculations of OTA as well as OTD for a large sample of hail events in the U.S. will be presented.

We are also exploring how our interpretation of the OT–updraft and thus OT–hazard relationships may depend on the thermodynamic characteristics of the upper-troposphere/lower stratosphere (UTLS). Observations collected during the RELAMPAGO field campaign show that OTD is highly correlated to UTLS static stability, implying that updraft penetration into the stratosphere is reduced with an increasingly stable UTLS. In contrast, OTA is relatively insensitive to the UTLS static stability.

Differential reflectivity columns and hail-linking C-band radar-based estimated column characteristics to a uniquely large dataset of crowdsourced surface observations in Switzerland

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It has been shown that differential reflectivity columns (ZDRC) are a radar signature that can be used to characterize the updrafts of severe convective storms. Consequently, various studies have attempted to link ZDRC characteristics to severe weather development, such as tornado formation, intense precipitation, and hail. Much of this work, specifically on hail, has been done on case studies with limited ground truth hail data and using S-band radar data. Here, we investigate the characteristics of ZDRC automatically detected on an operational C-band radar network and relate them to hail on the ground using 173’000 crowdsourced hail reports collected over a period of 3.5 years in Switzerland.

The automated detection of ZDRC in the alpine region provides challenges regarding visibility and data quality due to effects such as ground clutter and the shielding of the radar beam by topography. Further, ZDR measurements are affected by the effects of differential attenuation and artefacts such as three-body scattering. To counteract these effects, we derive a 3D composite of ZDR using all five Swiss weather radars, two of which are located at an altitude of close to 3000 m above sea level. This composite is then used to identify ZDRC by an adapted version of an established detection algorithm.

The detected ZDRC areas and heights, as well as maximum measured ZDR values, are linked to reported hail size categories, and we attempt to determine thresholds to differentiate between storms producing hail of different sizes and non-hail-producing storms. Further, we investigate the potential of ZDRC to nowcast hail for possible warning applications. Switzerland is a unique location for this work due to the high frequency of hail, the good overlap of the radars, the scanning strategy with an exceptionally high spatial and temporal resolution and the large number of hail reports from the population.

Updraft characteristics of hailstorms and their utility in hail size nowcasting

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Weather radars allow the real-time tracking of hailstorms and the timely issuing of warnings, but accurate hail size detection poses a major challenge due to resonance backscattering once hail reaches a critical size. Over the past decades numerous radar-based methods for assessing maximum hail size have been proposed. A common approach is to derive hail scores from radar reflectivity (ZH) at multiple levels, one example being the “Maximum expected size of hail” (MESH; Witt et al., 1998). Other methods utilize a combination of ZH and polarimetric variables, or radar-derived proxies for updraft strength like storm-top divergence. However, all methods encounter difficulties particularly in the upper end of the hail size spectrum.

Aiming at filling this knowledge gap we analyzed hailstorm updrafts, detected by a ZDR based method. Using data from the WSR – 88D NEXRAD radar network and hail reports from the Storm Prediction Center (SPC) we compiled a large dataset of more than 100 case days with hail up to 17 cm in size. We then evaluated various radar variables possibly related to the presence of hail or the updraft's potential to promote large hail growth. We compared their statistical distributions for different hail size categories to infer the relation to hail size. Based on these data we trained a Random Forest model to nowcast different hail size categories, achieving a Peirce Skill Score (PSS) of 0.44 for nowcasts 20 minutes prior to hail observations. This surpassed the PSS of MESH at the time of hail observations and had higher accuracy in detecting giant hail.

Investigating the predictability link between heatwaves and severe convective outbreaks in Europe

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Recent summers in Europe were accompanied by significant convective storm outbreaks with widespread large hail, flash floods and severe wind phenomena. Particularly severe outbreaks have occurred at the breaking point of multi-day heatwaves, leading to considerable compound hazards from heat and drought meeting severe thunderstorms. The decay of blockings and heatwaves remains one of the largest forecast uncertainties and shows ties to the onset of widespread convection.

Utilizing reanalysis data, we investigate the link between blocking patterns, heat anomalies and the decay of blockings with respect to severe convective environments. This analysis reveals that severe thunderstorm environments across Europe are preceded by multi-day heat anomalies and a slow-moving upper-level wave pattern. With the predictability of blockings and heatwaves extending to several weeks, improved understanding of their evolution and following convective outbreaks is imperative to advance the predictive skill of severe convection.

Advancing the understanding of links between large-scale processes and meso-scale convective clusters sheds light on the reasons for current limits in forecasting convective outbreaks and highlights possible windows of forecast opportunity, where predictability can be extended.

Global hail distribution as observed by GPM DPR

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Scientists have dedicated great efforts to study hailstorms due to its destructive impact. An extreme hailstorm can cause billion-dollar losses in only several minutes. A vertical description of the profiles of precipitation is a long-term goal of atmospheric research and precipitation science.

In the new version of GPM (Global Precipitation Measurement) DPR (Dual-frequency precipitation radar) algorithm (version 7), a hail product ("flagHail") is developed in the classification module to identify hail along a vertical profile. The novelty of this algorithm offers the potential for retrieving a uniform and homogeneous hail dataset on the global scale from spaceborne radar sensor. The algorithm is built upon the precipitation type index (PTI) developed for the GPM DPR. PTI has been shown to be effective in separating various precipitation types such as snow, graupel and hail profiles. The capabilities of this algorithm to capture hail are validated by analyzing hail observations from various space and ground sources. These include ground validation radar NEXRAD, GMI based hail identification and multiple scattering effect from Trigger module of DPR level-2 algorithm.

A global hail map is generated using this hail product and the map is cross-compared with the hail map generated with either GMI-based approach or other statistical models. Common hot spots of hail occurrence are spotted among various algorithms. The global scale analysis demonstrates the good performance of the hail algorithm in identifying the world-wide high frequency hail regions and seasonal transitions.

European record-breaking hailstorms in northern Italy on 19 and 24 July 2023

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During 12 – 25 July 2023 northern Italy was affected by six severe storm outbreaks, that caused about 4.0 billion of euros of economical damages, at least 280 injuries and 3 deaths. The European record of the largest hailstone was broken two times: the first one in Carmignano del Brenta (Veneto region) on 19 July 2023 (16 cm - large hailstone), the second one in Azzano Decimo (Friuli Venezia Giulia – FVG – region) on 24 July 2023 (19 cm - large hailstone).

In the evening of 24 July 2023 an exceptional outbreak took place with three violent supercells that swept Northeastern (NE) Italy, all generating giant hail. A radar analysis showed that those storms were characterized by an impressive Bounded Weak Echo region in the reflectivity field, and by a couplet of inbound and outbound velocities in the medium level, highlighting the presence of a mesocyclone.

The synoptic configuration of the two days was similar, characterized by an intense and moist southwesterly flow in the Mediterranean region, located between a sub-tropical ridge and a trough over western Europe. On the other hand, surface conditions in the NE Italy were different during the two events, with much higher values of equivalent potential temperature (theta-e) on 19 July 2023 (about 350 K) than on 24 July 2023. During this latter event, before the record-breaking hailstorm at 2100 UTC, just 330 K of theta-e were observed in the plain. An atmospheric sounding launched at 1700 UTC on 24 July 2023 showed that also the convective potential instability was quite low in the FVG region, while the vertical wind shear and the storm relative helicity were very strong. We hypothesized that the intense and moist southwesterly flow was an essential feature for the development of the violent supercells, while surface thermodynamic conditions were not detrimental.

Impact of initial condition and cloud physics perturbations on predictions of convective storms and associated hail

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Formation and growth of hailstones strongly depends on the dynamic and cloud microphysical structure of convective storms, which are known to vary substantially with thermodynamic conditions during storm initiation and development.

An analysis of the impact of initial condition and cloud physics perturbations on the prediction of convective storms and hail in the Munich area on 10. 06. 2019 is presented. The analysis is based on a high-resolution combined initial condition and perturbed cloud physics ensemble with the ICON model. Both types of perturbations are found to have a substantial impact on the simulated convective storms, their structure and lifetime as well as the occurrence of conditions conducive to hail formation. However, the fraction of precipitation that arrives as hail at the surface is much more strongly influenced by cloud physics perturbations compared to initial condition perturbations. To provide further insight into the impact of varying cloud dynamics and structure on hail growth and trajectories we present results from a Lagrangian hail model integrated during the ICON simulations.

Exploiting DWD's operational C-band radar birdbath scan for quantifying hail characteristics

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Hailstorms can cause significant damage to personal property and public infrastructure, depending on storm attributes such as hail size, amount, or kinetic energy. Yet, estimates of these hail characteristics at the ground or aloft derived from current in situ observations or remote sensing methods are fraught with high uncertainties that are difficult to track and quantify. This presentation will give an overview of how Doppler (power) spectra that are routinely recorded for DWD's (vertically looking) birdbath scan since 2021 can be used to retrieve the full hail size distribution and then estimate crucial hail characteristics for hailstorms that pass over a radar site. Based on previously published hail size-to-fall-velocity relationships, Doppler velocities can be converted into hailstone diameters; and the Doppler spectra can be translated into hail size (frequency) distributions after simulating the radar backscatter cross section for each hail size. Finally, relevant hail characteristics can be determined. Hail microphysical properties that are required as input for the retrieval method (e.g. hail size-to-fall-velocity relationship, hailstone shape or density) can be modified easily and the associated uncertainties in the hail characteristics can be assessed. The presentation focuses on estimating the typical and the maximum hail size, the hail kinetic energy content, and the hail rate. For three analyzed hailstorms, we retrieve maximum hail sizes of about 2 to 4 cm, in agreement with eye witness reports. The uncertainty analysis shows the highest uncertainties for estimated hail kinetic energy content and hail rate, while retrieved maximum and typical hail sizes are generally less sensitive to the assumed hail microphysical properties.

A wind tunnel investigation of the melting of hailstones – Part II: Implications for hailstone size distributions measured at the ground

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The properties of hail: the size distributions, their fall velocities, masses, and kinetic energies, change significantly as they fall from the melting layer to the surface. Factors such as the altitude of the 00° C isotherm, the depth of the melting layer, temperature, and relative humidity profiles from the base of the melting layer to the surface, and the altitude at ground-level, all significantly affect the melting of hail.

The T-28 hail penetrating aircraft collected hail size distribution (PSD) and state parameter data from penetrations into hailstorms at temperatures below 0 ° C over the period 1972 – 2003. To further quantify the significance of these data for mapping out the change in the hail PSD from the melting layer to the surface and for developing relationships to quantify melting hail with radar, reliable calculations of the melting of hailstones are needed.

Toward this end, experiments of the melting of realistic hailstones were conducted in the University of Mainz vertical wind tunnel. Rather than using spherical, solid ice hailstones as in past laboratory hail melting experiments, molds produced from 3D-printed real hailstones were developed, and then filled with water to provide the hailstones for the melting experiments. The sizes ranged from 0.5 to 2.0 cm. A hailstone was suspended in the wind tunnel and exposed to either a constant temperature above freezing or a temperature profile mimicking an actual atmospheric temperature from the melting layer to the surface. The particle was photographed, and its mass measured at several times as it melted. The results of these melting experiments will be presented and compared to earlier laboratory and modeling studies that assumed spherical hail. The parameterizations developed will be applied to the T-28 PSD to assess how the hail PSD evolve as they fall from the melting layer to the surface.

Implementing physical assumptions about nonspherical hailstone shapes

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Numerical modeling is valuable in hail research and forecasting. Physical assumptions regarding hailstones' shape, tumbling behavior, fall speed, and thermal energy transfer are applied in this process, be it explicit or inexplicit. In this study, we investigate the effect of applying different physical assumptions in hail modeling using Cloud Model 1 to simulate supercell storms, coupled with the detailed 3D hail growth trajectory model by Kumjian & Lombardo (2020; hereafter KL20). We then examine the reason behind the variability in hail statistics produced with these assumptions.

Most microphysics schemes and hail models assume hailstones are spherical (e.g. Morrison et al., 2005; Adams-Selin and Ziegler 2016; KL20). Using hailstone shape data from Heymsfield et al., (2020) and Shedd et al., (2021), we establish a relationship between the hailstones' mass or equivalent spherical diameter and shape with reasonable degrees of randomness, capturing the observed distribution of tri-axial ellipsoidal shapes. We also incorporated explicit, random 3D tumbling of individual hailstones during each timestep of their growth to simulate the behavior of free-falling, non-spherical particles (Bagheri & Bonadonna, 2016) and the resultant changes in the collection kernel. These physical attributes are then incorporated in calculating the hailstone's terminal velocity, using either empirical relationships or analytical relationships based on each hailstone's Best number and Reynolds number. Options for drag coefficient modification are added to characterize the hailstone's rough surface with varying degrees of "lobiness". The hailstone's shape and "lobiness", in turn, modify its thermal energy transfer coefficient (Macklin, 1963; Bailey and Macklin, 1968). We find the choice of hailstone diameter-mass relation, and terminal velocity scheme to have the strongest influence on final hail size. Using non-spherical, tumbling hailstones tends to reduce the number of large hail produced in our simulated supercell storms; applying shape-specific thermal energy transfer coefficients tends to increase final hail size by a small amount; the effect of lobes varies depending on the terminal velocity scheme used. We show that many of these physical assumptions, albeit adding complexity to hailstone growth modeling, can be parameterized efficiently and potentially used in bulk microphysics schemes.

How do updraft width, intensity, and water content influence hail size in toy simulations?

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Hail growth in supercells has recently been studied with numerical simulations and detailed 3D hail trajectories (e.g. Kumjian and Lombardo, 2020). The goal is to understand how different atmospheric environments lead to dynamical or thermodynamic changes in the supercell, thereby influencing hail. One difficulty with this approach is that changes in the environment often result in multiple complex feedbacks in the storm. For instance, increasing CAPE may increase the updraft velocity but also impacts liquid water content, horizontal winds, hydrometeor production, and others (e.g. Lin and Kumjian 2022). This makes it hard to disentangle which of these factors contributed to a change in the hail size spectrum and why.

Hence, a more idealized approach is used in this study. The updraft is directly controlled with a heat source (e.g. Markowski and Richardson 2014). Furthermore, the simulations are run in dry mode so moisture fields are also directly parameterized around the updraft. Hail trajectories are then calculated following Kumjian and Lombardo (2020). This simulation setup is ideal to investigate the effect of updraft or moisture characteristics on hail growth independently and systematically. In the first two experiments, updraft width and updraft intensity are varied independently. Preliminary results indicate that the updraft width greatly influences maximum hail size and amount but only up to a certain width, consistent with previous studies (Lin and Kumjian 2022). In a third experiment, we investigate how hail growth reacts to increasing liquid water content as expected in the future climate.

A modeling case study of a severe hail storm in complex topography

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On 28 June 2021, Switzerland experienced the passage of a formidable supercell, navigating its complex terrain. Over a span of 350 km and a duration of 8 h, this supercell unleashed severe hailstones measuring up to 9 cm in diameter. We present a comprehensive case study aimed at unraveling the complexities surrounding the genesis, amplification, and dissipation of this impactful weather event. To this end, we investigate ensemble hindcast simulations using the COSMO-1E numerical weather prediction model that includes the HAILCAST hail growth parameterization. The model setup for these hindcast simulations is identical to the one for the operational ensemble forecasts conducted by MeteoSwiss. A specialized tracking algorithm facilitates an object-based analysis of the simulated hail cell, addressing the inherent challenges in tracking hail storms within numerical simulation outputs.

By scrutinizing the storm's evolution across various phases, particularly during intensification, the study conducts a storm-relative analysis of 119 simulated supercells with lifetimes of > 2.5 h, delving into the storm environment's temporal dynamics. Furthermore, the investigation utilizes Lagrangian air parcel trajectories initiated along the hail track to analyze the inflow of air sustaining the storm updraft. This exploration provides fresh insights into the low-level flow patterns and moisture sources contributing to the storm's vigor. It reveals the importance of topographical features for the initiation and dissipation stages of the storms.

The analysis focuses on the intensification and dissipation phases, aiming to unravel governing processes. In essence, this study aims to shed light on the intricacies of supercell development within Switzerland's complex topography, offering a nuanced understanding of the storm's lifecycle.

Impact of aerosol and microphysical uncertainty on the evolution of a severe hailstorm

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Forecasting high impact weather events is a major challenge for numerical weather prediction. Initial condition uncertainty plays an important role but so do uncertainties arising from the representation of subgrid-scale processes, e.g. cloud microphysics. Here, we investigate the impact of cloud microphysical parameter uncertainties on the forecast of a selected severe convective storm over South-Eastern Germany in 2019, which is generally referred to as the Munich hailstorm (Wilhelm et al., 2020). The storm is simulated using the ICON model (2-moment cloud microphysics, 1 km grid-spacing) with perturbed microphysical parameters related to graupel and hail formation. Combinations of parameter perturbations are chosen according to a Latin hyper cube design and one-at-a-time parameter perturbations for the smallest and largest parameter values. Important impacts on surface (hail) precipitation are found for parameters pertaining to (i) CCN and INP activation, (ii) diffusional growth of ice, and (iii) the mass-diameter and mass-fall velocity relations for graupel. The behavior of graupel particles are thereby controlled by their density. The one-at-a-time parameter perturbation simulations are used to track microphysical process rates. By closing the hydrometeor mass budgets we explore changes in precipitation formation pathways (based on the approach by Barrett and Hoose, 2023) arising from perturbations of the most impactful parameters. Preliminary results show a strong influence of graupel density on the hail particle size distribution as well as total precipitation, but less so on surface hail amount. The analysis allows us to draw conclusions about the most impactful cloud microphysical parameters for hail forecast uncertainty as well as the underlying mechanisms.

CCN effects on hail and its uncertainty evaluation compared with initial meteorological condition

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The uncertainty of the cloud condensation nuclei concentration (CCNC) effect on hail precipitation due to perturbed initial meteorological conditions (IC) has been evaluated using an ensemble data from an idealized hailstorm by the high-resolution Weather Research and Forecasting (WRF) simulation. Varied CCNC from clean to polluted condition in six concentrations with uneven intervals resulted in a curve pattern that increasing firstly and then decreasing with single peak for hail precipitation rate. Vertical sensitive simulations showed that CCN at 750 – 800 hPa plays a dominant role in the change of hail rate, while the total precipitation is dominated by 700 – 800 hPa height CCNC. However, we found some tiny perturbed ICs from ECMWF, including thermodynamic (TQ, potential temperature and mixed water vapor ratio) and kinematic condition (UV, U wind speed and V wind speed), can even change the curve style with multiple peaks, indicating a potential large uncertainty for CCNC effect on hail in an uncertain IC. Although the meteorological perturbations produce large uncertainties in both hail and total precipitation, varying CCNC by an order of magnitude causes even larger uncertainties than the meteorological perturbations. Changing CCNC modifies the predictability of hail precipitation, with higher predictability in moderately polluted environments compared with very clean and polluted environments. Perturbing the initial meteorological conditions does not qualitatively change how aerosols affect hail and total precipitation.

Isotopic analysis for tracing vertical growth trajectories of hailstones

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The growth trajectory of hailstones within clouds has remained elusive due to the inability to trace them directly, impeding comprehension of the underlying growth mechanisms. Using stable isotopes as proxies, we can capture the ambient temperature of supercooled water that freezes within the hailstones and, therefore, examine the hailstone growth process's altitude by detecting stable isotope signatures in each hailstone layer. Twenty-seven hailstones were analyzed from nine different hailstorms by examining their bubble structure. The deuterium and oxygen-18 content was then measured using a cavity ring-down spectrometer. The isotopic content of water condensate in the cloud was calculated using an adiabatic model. Although hailstone growth is found in the – 10 °C to – 30 °C layer, the height of the embryo's formation and subsequent growth trajectory can differ significantly between hailstones. Of these, three experienced little vertical movement, sixteen went through a monotonous rise or fall, and the remaining eight showed an alternating up-down trajectory, with one performing recycling up-down drifting. The radar-based hydrometeor phase identification results confirm the vertical trajectory inversion results. These findings propose that multiple patterns exist for the hailstone growth tracks.

Hailstones falling through a cloud of supercooled droplets: No evidence of efficient ice multiplication

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Formation of hailstones in thunderstorms is closely associated with ice multiplication via rime-splintering, also known as Hallett-Mossop (HM) process. The understanding of secondary ice production (SIP) mechanisms is therefore essential for a reliable description of convective cloud dynamics, prediction of precipitation, and hail warnings. We report an experimental study of rime-splintering under conditions representing convective mixed-phase clouds in the temperature range of $-4\,^{\circ}$C to $-10\,^{\circ}$C, conducted in a recently developed experimental setup IDEFIX. The setup allows for high-speed video observation of the riming process and IR thermographic measurements of the hailstone surface temperature. Potential secondary ice (SI) particles were captured in a supercooled sucrose solution where they could slowly grow to visible size. Riming in both, dry and wet growth regimes was investigated with no apparent evidence of an efficient SIP, in contrast to some earlier studies where up to several hundreds of SI particles per mg rime were found at ambient temperature of $-5\,^{\circ}$C. Analysis of our experimental results allowed us to exclude two potential ice multiplication mechanisms underlying the HM process: freezing of droplets upon glancing contact with the hailstone and fragmentation of droplets freezing on a hailstone. A break-off of sublimating fragile rime spires has been shown to produce very few secondary ice particles, insufficient to account for large numbers of ice particles reported in earlier studies. During the transition between wet and dry rimer growth regime, formation of spikes on the rimer surface has been observed, a potential SIP mechanism associated with the pressure rise in water trapped under the freezing shell. This mechanism of spike formation is analogues to the phenomena of deformation of drizzle droplets upon freezing.

The impact of hailstone shape on hail trajectory stochasticity

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Recent research has suggested that identifying common trajectory pathways that hailstones take through a storm is highly difficult given their extreme variability, particularly on an individual storm scale. However, much of that research used a trajectory model that assumed a spherical hailstone shape, which does not align with observed hailstones. What impact does the inclusion of oblate spheroidal hailstone geometries have on in-cloud hailstone trajectories?

A set of idealized supercell simulations was generated by the CM1 cloud model of a pair of left- and right-moving supercells from the 29 May 2012 Kingfisher, Oklahoma, USA storm observed during the DC3 field campaign. The HAILCAST hail trajectory model (Adams-Selin and Ziegler, 2016; Adams-Selin, 2023; Pounds et al., 2023a) has been updated to include the option of oblate spheroidal hailstone shape (Pounds et al., 2023b). These updates include changes to the cloud water and ice collection, terminal velocity, and heat balance equations to account for the new cross-sectional area and heat transfer rates. Four-dimensional HAILCAST hail trajectories, both with and without these updates, were seeded across both supercells every 5 minutes from the time the storms reached maturity until just prior to dissipation. Only trajectories that started in a region with cloud water and/or ice and resulted in non-negligible hail growth were retained, but the number still summed in the millions.

This hail trajectory set was then analyzed in both the aggregate, using statistical methods, and via a density-based clustering technique to group the trajectories based on updraft-relative spatial location and orientation. In the aggregate, amount of time spent in wet/dry growth, in various temperature regimes aloft, and in specific updraft and horizontal wind magnitudes were calculated and compared across the right- and left-moving supercells and for spherical and oblate spheroidal hailstones. With the clustering technique, multiple common trajectory pathways were similarly identified to examine their changes due to supercell mode and hailstone shape. Finally, separate sensitivity tests were conducted to examine whether the collection cross-sectional area, heat transfer rate, or terminal velocity modifications for oblate spheroids were most impactful in changing the distribution and characteristics of the resulting hail trajectories.

An exploration of hail melt sensitivities using hail trajectory models and observations

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A unique hail dataset was obtained in the United States in the 1990s and early 2000s when an armored T-28 aircraft, operated by the South Dakota School of Mines & Technology, flew through powerful hail-producing storms. This aircraft flew between 0 °C and −12 °C and was outfitted with a Laser Hail Spectrometer capable of measuring hailstones between 0.45 and 5 cm in diameter. This one-of-a-kind dataset provides us with in-cloud hail size distributions before significant melting.

We have used the hail size distributions obtained from the T-28 to initialize a modified one-dimensional version of HAILCAST, a hail trajectory model focusing only on hail melt. The simulated hail is allowed to have variable density, mixed phases, retained surface water, and shed drops. Melting and terminal velocity parameterizations are only included. However, accretion and other growth processes are excluded. This modified version of HAILCAST has been connected to a polarimetric radar simulator and we are working toward comparing our simulated profiles to observed radar profiles.

For each T-28 flight, an ensemble of simulations is run to explore how sensitive the results are to different melting and terminal velocity parameterizations, environmental conditions, and updraft speeds. The results of these sensitivity tests highlight the need for additional research and data on hail melt.

Characterizing hailstones from different storm modes: A novel method for analyzing physicochemical properties of non-soluble particles in hailstones

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Hailstorms cause significant damage and economic loss in convectively active regions worldwide. It is crucial to study hail-producing storms from a global perspective due to the limited understanding of the environmental conditions and variation in storm modes associated with hail-producing storms. However, this task is challenging partly due to the lack of understanding of the role of environmental aerosols acting as CCN and INPs in hail formation. This study presents a novel method applied to hailstones collected near Cordoba, Argentina, that preserves in situ non-soluble particles for physical and chemical analysis. The method is composed of two techniques: trapping non-soluble particles beneath a plastic coat by using an adapted sublimation technique and then analyzing the particles with both Confocal Laser Scanning (CLSM) and Scanning Electron Microscopes with Energy-Dispersive Spectroscopy (SEM-EDS). These techniques provide physical attributes, including size and surface topography, and detailed information on individual particle elemental chemistry, enabling classification based on composition. This study investigated two distinct hail-producing events: firstly, an isolated supercell storm, producing a 4 cm hailstone, that emerged over the northern section of the Sierras de Cordoba (SDC) in central Argentina. Secondly, a mesoscale convective system (MCS) developed near the southern section of the SDC, producing an 8 cm hailstone.

The CLSM particle size distribution analysis for the isolated supercell revealed sizes ranging from ∼2 to 150 µm, while SEM-EDS elemental composition analysis showed that carbonaceous particles were the most abundant category compared to particles categorized in the silicates and salts groups. Airmass back trajectory analysis linked to the composition results suggested that the hailstone's particles likely originate from regions with mixed vegetation and croplands near the SDC, with potential contributions from mountain erosion and agricultural topsoil. The particle size distribution analysis for the MCS revealed even larger particle sizes than the supercell case, with some exceeding 200 µm near the embryo. This presentation will further compare the elemental composition and potential source regions between the two events (i.e., supercell vs. MCS) and highlight the broader applications of this work related to hail formation and growth.

Identification of the causes in the increase of hail records in Catalonia since 2010

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Hail records in Catalonia have increased notably since 2010, as in many other European regions or from around the Globe. Records go from less than 0.5 cm to up to 10 cm and they also include the location and the date of occurrence. The purpose of this analysis is the evaluation of the main factors that have let to this increase: the campaigns conducted by the Meteorological Service of Catalonia (started in 2016), the irruption of social networks, or the rise in the number of official spotters from the Catalan meteorological service.

On the other side, future climatic scenarios are not coincident for Catalonia, but in most cases indicate an increase of large hail events and reduction of the small hail cases. To confirm this trend for the last years, the previous registers have been com pared with other objective elements, such as the VIL (Vertical Integrated Liquid) radar fields or the lightning jump occurrences, to determine the real increase of both type of registers (small and large). Then, each event has been classified according to the maximum hail size recorded and the maximum hail size estimated from remote sensing data. This has allowed normalizing the occurrence series and answering the proposed questions that lead this analysis.

A case study of the evolution of severe hail thunderstorm developed over Bulgaria on 06 August 2023 in relation to hail suppression

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A severe thunderstorm developed over Bulgaria on 06 August 2023. The storm crossed over the length of the whole country and passed over 300 km maintaining high radar characteristics for more than 5 hours. Hail suppression operations were carried out in South Bulgaria by rockets and in North Bulgaria by aircraft with glycogenic agent.

The synoptic scale situation combined with high atmospheric instability determined the environmental conditions over Bulgaria favorable for the development of severe convection. The seeding operations by rockets began in the initial stage of the thunderstorm development and continued for two hours. After leaving the territory protected by rockets, the seeding continued by aircrafts for more than one hour. Then the seeding area entered the Terminal Maneuvering Area of Varna airport, in which the flight was prohibited. During the time of the hail suppression operations, information for small hail stones less than 1 cm in size in isolated locations without damage was reported. Twenty minutes after the stop of the seeding, the maximum radar reflectivity reached 71 dBZ and severe large hail up to 5 cm in diameter was reported for more than 30 minutes. The hailstones have almost completely destroyed the vegetable and fruit plantations. An analysis of the evolution of radar characteristics of the thunderstorm during its lifetime will be presented with an emphasis on the difference in them between the seeding and no-seeding periods.

Analysis of radar characteristics of seeded and non-seeded hail cells developed over Bulgaria

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Geographical location and climate features determine Bulgaria as one of the countries with high frequency of hail damage. A hail suppression program in Bulgaria is carried out for more than 50 years and is based on the physical concepts of the beneficial competition and early raining out of the feeder cells. Radar information from seven S-band Doppler radar stations is used for hail suppression operations.

The aim of the present work is to reveal if there is a pronounced difference between radar estimated characteristics of seeded and non-seeded hail cells. Radar data from hail cells developed over Bulgaria in the period 2020-2023 was used. Two equally-sized samples (15 seeded and 15 non-seeded cells) were selected. All analyzed cells had vigorous development with supercooled part of 45 dBZ contours (dH45dBZ) higher than 6 km and maximum radar reflectivity higher than 60 dBZ during their lifetime.

The results from the comparison of various radar estimated characteristics (e.g. height of 45, 55, 60 dBZ contours, maximum radar reflectivity, surface rain intensity) between the two samples will be presented. Additionally, a case – by – case comparison was performed for seeded and non-seeded control hail cells. To do that the best match between the trends of growth of dH45dBZ in the initial development of both cell types was chosen. Cells with a match difference of less than 15 % were examined further.Evolution of radar characteristics of both cell types during their lifetime will be analyzed and presented.

Developing a synthetic hail event set for risk assessment

Jana Löffelmann[1], Thomas Hofherr[1], Anja Rädler[1], Mirjam Hirt[1], Peter Miesen[1], Alex Allmann[1]

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Severe convective storms with large hail and strong winds pose a great danger to human life and property. Every year, hail causes billions of dollars (USD) in crop and property damage worldwide. We facilitate the evaluation of hail risks over Europe by developing a synthetic hail event set. First, a convective hazard model (AR-CHaMo, from ESSL) estimates hail probabilities based on ERA5 reanalysis data, where trends have been adapted to match the today's climate. Based on these hail probabilities, stochastic hail events can be triggered every 6 hours. The characteristics of these hail events are then modeled after realistic hail events by considering a variety of different data sources. Historic hail tracks over Germany based on vertically integrated ice from the Deutscher Wetterdienst (DWD) provide size distributions of the hail tracks. Additionally, the maximum hail diameter for each synthetic hail track is derived based on a preassigned relationship between the ERA5 atmospheric conditions and ESWD hail reports. And, by combining loss data and ESWD hail reports we obtain spatial patterns of hail diameters.

Using 200'000 years of statistically simulated hail tracks, we can derive hazard maps for selected return periods and, in combination with exposure information and a vulnerability module, the actual risk of damages can be estimated.

Damage to crops caused by hail in Serbia

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Hail typically occurred less than once per year at 75 % of hail suppression stations in Serbia. In about 75 % of events, hailfall lasted less than 5 min and only 8 % of events lasted more than 10 minutes, according to data between 1981 and 2015. From these figures, one could conclude that the hailfall cannot cause such great damage to human society. Of course, that is just a subjective impression. Hail is a weather phenomenon that can and does cause significant damage to material goods, crops, infrastructure, and motor vehicles. To mitigate these damages, cloud seeding in Serbia has been in use since 1967. The operational system consists of 13 radar centers on which area was evenly distributed rocket launching stations. Educated staff at the launch stations monitor hailfalls, their duration, thunder, showers, and rain.

The source of our data is the municipal services and the commission of experts of the Republic Hydro-meteorological Service of Serbia. The damage only concerns that to agriculture, actually damaging crops from the individual and municipal fields. We analyzed the collected data for the period 1981 to 2022. The average number of days with registered hail damage was 30.9. The lowest and highest number of days with damage was 18 (in 1987, 1990 and 2000) and 47 (in 2018) respectively. The average annual damaged area, regardless of the percentage of damage, is 80,501 ha, which corresponds to 1.57 % of the agricultural area. The average annual damaged area reduced to 100 % damage is 37’477 ha, which corresponds to 0.73 % of the agricultural area. In most cases, a large percentage of the damage occurs on only a few days in a year, which means that the large annual number of days with damage is not proportional to the extent of the damage.

Automation of the hail suppression system in Serbia

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Hail suppression in Serbia has been in use since 1967. The operational system consists of 13 radar centers, on which area was evenly distributed rocket launching stations.

In 2019, the automation of the launch station network began. With automation, resources are used more efficiently, the ARLS (Automatic Remote Launch Station) network is smaller and more efficient, the number of executors is reduced, the stoppage in the firing of rockets is eliminated and the delay of actions is eliminated.

Automation has so far covered 5 of the 13 radar centers in Serbia, with a total of 532 ARLS, complete at 4 centers "Valjevo", "Fruška Gora", "Bajša", and "Samoš" with 488 ARSL (Automated Remote Launch Stations) and the first phase at RC "Bukulja" with 44 ARLS. Automation of the entire network of launch stations is planned from 2024 to 2028.

Sharing insights from coordinating and recent developments in hail defence operations in Styria Province, Austria

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The agricultural sector in the Styria province of Austria is grappling with a formidable challenge: crop hail damage. In response, Styria has engaged in extensive hail prevention experiments over the years, aiming to mitigate the adverse impact of hail on agriculture. This presentation will deliver the historical context and recent advancements in refining the operational framework. The hail defence platform is supported by eight aircraft and two radars. Operational planning and execution leverage various tools, including weather forecasts, radar data, aircraft tracking, data transmission, and a Tablet-PC display system integrated into the aircraft. Introducing a novel pilot visual interface communication system has further enhanced coordination efforts. Daily operational coordination planning involves meticulous allocation of aircraft and pilots, determining the anticipated mission commencement based on synoptic meteorological conditions, and assessing the current weather forecast and nowcast status. The Weather Information System (WIIS) software supports operational activities. Additionally, the HAILSYS software, tailored for post-analysis of daily operations and radar-derived parameters over time, will be presented, providing insights into changes attributed to cloud seeding. A crowdsourcing platform named HeDi (Hail Event Data Interface) was developed by TU Graz and actively employed for the expeditious reporting of hail events and crop damage information. This all-encompassing overview will delve into the sophistication of hail prevention operations, coordination protocols, recent advancements, and the nuanced challenges encountered in detail.

Global hail hazard modeling framework

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A global hail hazard modeling framework based on supervised machine learning has been developed. The modeling framework combines ground-based hail observations from the U.S., Canada, Europe, Australia, China, and Vietnam with environmental variables derived from global reanalysis and satellite data and allows for detailed hail hazard mapping on regional or global scales. Prognostic variables including the annual exceedance probability and return periods of hail size and kinetic energy. The global hail model reveals the occurrence of damaging hail across most continents and specifically in North America, South America, Europe, Africa, Australia, and Asia. Initial validation work suggests a good alignment with global and regional studies as well as with the internal hail loss experience.

Co-occurrence of hail and heavy precipitation in Switzerland

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The co-occurrence of hail and heavy rainfall has the potential to lead to an increase in damages. For example, a dense cover of hail may clog drainage systems, consequently creating a situation favoring flooding by subsequent rain. In this exploratory study, we investigate this phenomenon of co-occurring precipitation types, first in a case study of the 28th of June 2021 in Switzerland, a day with substantial damages caused by convective storms, before following up with an analysis of the whole convective season of 2021.

For the co-occurrence analysis, we require data with high temporal and spatial resolution and good spatial coverage, which is challenging in the complex alpine topography. For both hail and rain, we use datasets produced by the Swiss weather radar network, which consists of five c-band radars at altitudes between 900 – 3000 m. Further, the rain dataset is created using rain gauge data to improve the accuracy of the radar-based rain estimates.

The case study showed that hail and rainfall co-occurred in large areas, with 88 % of the co-occurrence areas experiencing extreme rainfall within 10 minutes of each other. The proximity, large impact area, and high cumulative amount of rainfall after the hail likely contributed to the costly damages of the 28 June 2021 hail event. Further, the seasonal analysis has shown that the cumulative amount of rain after the first hail detection is significantly higher than before. However, these results are not homogeneous in space or time but exhibit regional variation. Additionally, we find that the co-occurrence of hail and rain is impacted by the estimated maximum hail size as well as by the presence of cold fronts. Finally, we also explore the reliability and limitations of using radar data for the estimation of both hail and rain, e.g. addressing the challenge of errors in radar rainfall estimates arising from the presence of hail stones.

Recent spatial distribution and frequency of hail precipitation in Bulgaria

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Hail precipitation is a frequent event in many parts of the world, especially in mid-latitudes, and generally, damages caused by them present a significant part of the damage from natural disasters for many countries. The regions most affected by this extreme phenomenon in Europe extend from the northern parts of the Iberian Peninsula through the Apennines and Central Europe to the Balkan Peninsula. Not only the geographical location but also the complex orography of Bulgaria ranked it as one of the most hail-stormy countries in Europe. Since the beginning of the 21st century, there has been a tendency to increase the intensity and severity of hailstorms, which often result in significant damage to property and agricultural production. The present study aims to assess the spatio-temporal variation of hail days in Bulgaria during the period 1991 – 2022 using the Ordinary Kriging method for spatial interpolation in the QGIS environment. To identify the municipalities most vulnerable to hail precipitation, the zonal Statistics tool was applied to calculate selected features at the municipality level. A comparative analysis of hail precipitation in selected meteorological stations representative of each administrative district for two 30-year periods (1961 – 1990 and 1991 – 2020) is also presented. The results show no statistically significant differences between the two periods for the greater part of the stations. However, in some districts from the central northern and eastern parts of Bulgaria, a statistically significant increase in the frequency of hail days was observed.

Hail climatology, trend, and hazard models for South America and Australia

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Severe convective storms over South America are among the most intense worldwide (e.g. Zipser 2006) but less researched compared to the US, Europe, or Australia. For instance, the climatology of hail across the continent is somewhat uncertain, mainly because of limited homogeneous observations of hail. Similar uncertainties remain regarding the change in hail frequency in a warming climate (Raupach et al., 2022).

This study assesses both, the hailstorm climatology and trends over South America, based on a 28-year dataset of overshooting cloud top (OT) satellite observations (Khlopenkov et al., 2021). ERA5 Reanalysis data is used to exclude OTs in environments not supporting hail (e.g. Punge et al., 2023). Overall, the spatial distribution of these potential hailstorms is consistent with existing literature. However, some interesting differences stand out, such as a stronger than expected activity in southern central South America and in the foothills of the Andes compared to hail reports. Furthermore, preliminary analysis of the trend over this almost 30-year period indicates mostly weak and localized signals while the multi-year variations suggest a strong link to the El Ninjo-Southern Oscillation (ENSO).

An updated 3D radar-based hail statistic for Germany (2005 – 2023)

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Weather radars are the most powerful remote sensing tools for indirect hail detection. In particular, hail detection algorithms using volumetric (3D) radar reflectivity provide reliable estimates of hail on the ground (Allen et al., 2020). We present an update of an existing hail climatology for Germany (Schmidberger, 2018) by incorporating new data (new period: 2005 – 2023). Using the cell tracking algorithm TRACE3D (Handwerker, 2002), 3D radar data from the Deutscher Wetterdienst (DWD) were analyzed regarding specific hail signatures. The detected potential hail cells were tracked in each consecutive 15 min time step and formed contiguous hail tracks. Furthermore, filtering methods for the identification of hail tracks were improved (e.g., false detections, split and merge artefacts etc.). In addition to the spatial distribution of a grid-point based hail map, various characteristics of the hail tracks such as duration, length, width, direction and annual variability can be statistically evaluated over a period of 19 years.

Thunderstorm-hailstorm relationships and hailswath characteristics in Greece

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Hail is a major weather hazard with significant damage to agriculture but also to many sectors including infrastructure, automobiles and property. Hail damage potential is depended on the frequency and severity of hail occurrence and the vulnerability of exposed elements to hail threat. Economic losses of damaging hail have increased substantially last decades implying a possible climate influence.

Thunderstorm-hailstorm cell complex measurements are provided by weather radar and hailswath data by a hailpad network installed over an area of about 2,700 km^2 in central Macedonia, northern Greece. Weather radar and hailpad network are in operation since 1984 within the context of the Greek National Hail Suppression Program (GNHSP), an airborne cloud seeding program implemented by the Hellenic National Agricultural Insurance Organization (ELGA) for hail damage mitigation and reducing insurance payments to agriculture.

Radar data are provided by a C-Band weather radar operating continuously in 24 hours / 7 days a week during the hail season (March to September) of each year. In this work, a total number of about 1,560 thunderstorm-hailstorm cell complexes recorded in 440 thunderstorm-hailstorm days in the 13-year period 2011 – 2023 are analyzed. Radar parameters examined are thunderstorm-hailstorm cell complex time of occurrence, life time, cloud top, reflectivity, height of 45 dBZ contour, movement direction and speed and vertically integrated liquid water (VIL).

Hail data are gathered by a network of 157 hailpads with a mean linear spacing of about 4 km between sites in the Area 1 (2,700 km^2) of the GNHSP (prefectures Imathia, Pella, Pieria, Kilkis and Thessaloniki). In a total of 36 years (seasons) of hailpad network operation hail was recorded on 453 days and by 2,546 hailpads (point hailfalls). Hail parameters include number of hail days, hailpads recorded hail, maximum hail diameter, hail density, hailswath dimensions and hailswath area.

The results offer insights into thunderstorm-hailstorm relationships and their link to the characteristics of the hailswath on the ground. Fine scale hailstorm cell patterns as described by radar parameters are related to hail parameters offering some more knowledge about hail forecasting and destructiveness and therefore increasing potential to prevention and damage mitigation.

Machine learning algorithm for hail nowcasting in Northwest Bulgaria

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The hail thunderstorms are common across Europe and Bulgaria. Their timely forecasting is a challenge for forecasters and very important for hail suppression activities. The important moment in thunderstorm forecasting is the early and precise determination of convection initialization and development. Predicting the formation and development of vigorous thunderstorms producing heavy rain and hail is a complex process which among other environmental conditions depend on accurate estimation of water vapor distribution in space and time. In the last decade Global Navigation Satellite System (GNSS) derived Integrated Water Vapor (IWV) became an established observation technique in weather forecasting. Water vapor variation and distribution largely affects the formation and development of the thunder and hail storms. Preliminary research in Bulgaria showed that the combination of IWV and instability indices can be a good predictor of thunderstorm development. Since 2020, in Northwest Bulgaria 4 GNSS stations are running operationally and the data is processed in near-real time to compute the IWV. In this study, site-specific evaluation of thunder / hail storms is performed via Machine Learning (ML) for Northwest Bulgaria. A range of instability indices are calculated for each site using reanalysis data. These indices are then used by two ML techniques - Random Forest (RF) and Long Short-Term Memory (LSTM) models. The ML models were trained on a dataset spanning from 2020 to 2022 to distinguish between hailstorms and rainstorms. The results were then verified on the independent sample period of 2023.

Convective environments in AI-models – What have Panguweather, Graphcast and Fourcastnet learned about atmospheric profiles?

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The recently released suite of AI-based medium-range forecast models can produce multi-day forecasts within seconds, with a skill on par with the IFS model of ECMWF. Traditional model evaluation predominantly targets global scores on single levels. Specific prediction tasks, such as severe convective environments, require much more precision on a local scale and with the correct vertical gradients in between levels. With a focus on the North American and European convective season of 2020, we assess the performance of Panguweather, Graphcast and Fourcastnet for instability and bulk shear at lead times of up to 5 days. By advancing the assessment of large AI-models towards process-based evaluations we lay the foundation for hazard-driven applications of AI-weather-forecasts.

Investigation of climatic changes for hail storms over the Alps using spatio-temporal satellite imagery and self-supervised machine learning

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Severe hailstorms are becoming more frequent in Central Europe showing increasing inter-annual variability. The Pre-Alpine and Alpine region seems to be especially affected due to its complex terrain, that initiates convection and can intensify many hail favoring processes. This results in increasingly strong large hail events, which are often very local phenomena. Ground-based observations from weather radars are most reliable for detecting hail, however, prove to be challenging in the Alpine region due to interference at mountain ranges.

Passive Microwave satellite observations offer a useful alternative for detecting hail: a probability for hail can directly be derived from Passive Microwave channels with a high spatial coverage. However, this data is only available at certain times during satellite overpasses, thus, capturing only a few of these events. The highest temporal coverage is given by visible, near-infrared and infrared data from MSG. Though not directly sensitive to hail its high spatio-temporal resolution can identify early stages of severe storm developments.

Recently, self-supervised machine learning approaches have been used to classify spatial cloud patterns from satellite measurements from MSG over the Atlantic and Germany. The model learns to sort similar cloud organization patterns into the same classes.

In this work, we aim at adapting this model to also include the temporal component to then classify the evolution of typical cloud patterns leading to severe hail storms over the Alpine region. The framework will later be used to characterize changes in spatio-temporal evolution of large hail bearing systems and associated environmental conditions across a multi-year dataset. First steps are presented here including the investigation of the optimal training dataset using the available data sources.

Construction and feature analysis of surface hail report data set in China based on crowdsourcing

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The lack of dense hailstone observation networks is a common challenge worldwide, and alternative products such as weather radar are also faced with problems such as false or missed positives. Crowdsourcing is one of the possible ways to mitigate the problem, as hail identification can be easily accomplished even for people without meteorological expertise. Considerable hail reports can be collected in densely populated urban areas based on social media, with the potential to achieve high spatio-temporal resolution. In addition, since China has stopped the manual recording of hail from surface weather stations in the recent years, it is particularly necessary to build a localized surface hail database through crowdsourcing.

On Sina Weibo, China's leading social media platform, we have collected more than 100'000 Chinese reports related to hail each year. In Beijing from June to August 2021, for example, about half of the reports truly reflect hail events, which can correspond to strong convective systems identified on radar, while the rest ones are mostly related to past or non-local hail events. During longer-lasting hail events that swept across the city, such as the night of June 25, 2021, more than 600 reports were collected, the distribution of which reflects the fact that hail began at different times in different parts of the convective system.

Next, we plan to establish an effective screening mechanism for hail reports by introducing natural language analysis and other hail data sources through machine learning methods, and figure out the spatio-temporal distribution of hail reports based on Chinese social media. Crowdsourcing in weather is still in its infancy in China, so we also try to develop visualized small products to inspire people to participate.

Towards using artificial intelligence to estimate the occurrence and size of hail? Progress and challenges with the French dual-polarization radars

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Ongoing work at Météo-France is leveraging artificial intelligence (AI) in order to enhance hail detection and hail size estimation at the ground. Studying the morphology of dual-polarization variables on a sample of storms, the developed AI methods try to enhance the performances of well-known radar-based hail detection techniques applied to the whole French territory. To do so, a quality-controlled dataset of radar samples is built along with verified hail reports on the ground. As the performance of the developed AI methods is related to the samples in the dataset, challenges arise and precautions are needed when developing such a dataset to avoid a bias in the training. On top of the dataset, AI methods have a range of hyperparameters that have a significant impact on the results. Finally, given the relative scarcity of hail reports and the different sampling among sizes, additional precautions need to be taken to avoid a badly designed AI experiment. This work will present the challenges of building a dataset for hail detection and hail size estimation, the impact of hyperparameter tuning on the results and the overall precautions needed to maximize the value of AI methods.

Environments associated with hail production in subtropical South America

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Subtropical South America (SSA) is home to some of the most intense convection in the world as determined by depth of convection, size of organized convective systems, lightning flash rates, and satellite-estimated hail production. Recent research using TRMM-based hail detection and convective mode classification has suggested these SSA hail-producing storms differ significantly from their counterparts in the U.S.: they remain close to the nearby elevated terrain, suggesting an orographic link, and they tend to be organized or linear multicellular convective modes as opposed to the discrete supercells that more commonly produce hail in the U.S. The availability of GPM data over South American now offers the opportunity to revisit recently established SSA hail and convective mode climatologies, using the finer spatial resolution of the GPM data along with recent advancements in satellite-based hail detection algorithms. The addition of high-resolution GOES data offers an opportunity to directly interrogate convective updraft characteristics.

Using the Bang and Cecil (2019) hail detection algorithm for GPM, similar annual and diurnal cycle frequencies were found, with peak hail detection noted in the overnight hours. Precipitation features with a high probability of hail were still found to remain closer to orographical features, and were almost entirely classified as organized multicellular systems. All of these results, while similar to TRMM-based studies, are contrary to more typical U.S. hail-producing storms, suggesting potential fundamental environmental differences. To explore these environmental differences, ERA5 reanalysis data were obtained for each precipitation feature the GPM hail detection algorithm was confident either did, or did not, contain hail. Data from both set local times as well as from an hour prior to storm initiation were used to interrogate pre-convective environmental conditions at differing temporal scales. Storm initiation of each precipitation feature was determined using GOES ABI 10.3 mm brightness temperatures (Tb). Resulting environmental fields in the reanalysis data were mined for common environmental modes following both the global hail environmental analysis of Zhou et al. (2021) and the regional analysis conducted using Brazilian hail reports by dos Santos et al. (2023).

Stormforecast.eu: Real-time automated forecasts for hail and lightning based on post-processed NWP

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[1]European Severe Storms Laboratory (ESSL), Austria

The European Severe Storms Laboratory (ESSL) has developed logistic models (AR-CHaMo) for the occurrence of lightning and (very) large hail based on the ERA5 reanalysis, with the primary purpose of investigating long-term chance in severe weather occurrence. These models can, however, also be used in a forecasting context. We have set up a routine that uses AR-CHaMo models to post-process the output of three different NWP models, the ECMWF IFS HRES, DWD's ICON-EU, and NCEP's GFS to obtain probabilities of hail and lightning occurrence. The results were evaluated as a part of the ESSL Testbeds in 2022 and 2023. Forecast maps showing the calculated probabilities for the current and following day are calculated from the average of the three models and are made available on a website. The website interface allows overlaying reports from the European Severe Weather Database, which gives an impression of the quality of the forecasts and help to identify existing weaknesses. We show several AR-CHaMo lightning and large hail forecasts that resulted in no hail, large hail, and very large hail and discuss their performance. Work is underway to include ensemble forecasts, quantitative real-time verification, and to extend the forecast horizon as part of projects supported by the Austrian Science Fund and ECMWF. Preliminary results of these projects will also be presented.

Analysis of convective parameters associated with hail reports from the South American meteorological hazards and their impacts database

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Large areas of southern South America are recurrently affected by severe weather episodes. In particular, the thunderstorms that develop in the region present extreme characteristics in terms of the amount and size of the hail that can reach gargantuan dimensions. Recently, with the creation of the South American Meteorological Hazards and their Impacts Database (SAMHI), a vast amount of hail reports from multiple sources is continuously collected and recorded in a standardized manner. The creation of this dataset allows for comprehensive studies at a regional level, as is the one presented here, and is expected to provide the base for a growing body of severe weather research in the region.

Using 4244 hail reports from the SAMHI database, proximity soundings have been constructed with data from the ERA5 reanalysis, in order to characterize the convective parameter space associated with non-severe (< 2 cm), severe (≥ 2 cm) and significant severe (≥ 5 cm) hail. Overall, with an increase in the hail size category, there is a tendency for an increase in the magnitude of the convective parameters computed, although with considerable overlap among categories. In particular, composite parameters developed from observed conditions in other regions of the world such as the Significant Hail Parameter (SHIP) and Large Hail Parameter (LHP) do not provide a clear differentiation between the categories, and an adaptation to the local conditions may be needed to increase their utility in an operational setting.

The effectiveness of a continuous-wave radar to measure the fall speed of hailstones

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It has been decades since field measurements were last taken to measure the fall speed of hailstones. Consequently, accurately and reliably measuring the fall speed of hail remains a challenging and important problem. Recent advances in technology mean that we have access to new tools that can be used to address this challenge without having to rely on complex methods such as high-speed photography. Here we present results from tests to evaluate whether a small, continuous-wave radar (originally developed for the navigation of autonomous vehicles) could be repurposed to measure the fall speed of hailstones in the field. The radar's small size (about the size of a credit card), accuracy, ability to detect high velocities (up to 75 ms^{-1}) and low power draw are all promising features. We used a Mavic II Pro drone to drop four different-sized ice spheres (diameters of 17 mm, 27 mm, 44 mm, and 51 mm) from varying heights above the radar. The drop tests showed that the effective range and sampling volume of the radar both increased as the size of the ice spheres increased. Additionally, data from the drop tests showed that the radar had difficulty in detecting ice spheres with diameters smaller than 20 mm, and that it may not be effective at detecting any ice sphere that falls outside a radius of $\sim$55 cm of the radar. Overall, the radar has a large effective sampling volume relative to other hail sampling methods (e.g. a disdrometer), with an estimated sampling volume of $\sim$28 m^3 for a 51 mm ice sphere. We recommend configuring three or more radars in an array to increase the number of hailstones that can be sampled. Modifications to the signal processing may help increase the sensitivity of the radar to small hail.

Hail monitoring in Milan district by a network of dual-polarization X-band weather radars

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The Milan district in northern Italy is one of the most densely populated and urbanized areas in Europe and in recent years has experienced high-impact weather phenomena. The regional Agency for Environment Protection (Arpa Lombardia) installed a network of three X-band dual-polarization weather radars in 2022 with the objective of monitoring with high spatial and temporal resolution severe convection in the area. Severe storms that hit northern Italy with high precipitation rates, strong wind gusts, and large hail have characterized the summer of 2023. This work illustrates preliminary results of hail identification and hail size estimations obtained from X-band dual-polarization weather radar measurements. Local information on hit areas and hail size gathered from the ESSL database, local newspaper, and social media is used to validate radar POH and particle classification.

Wind shear as a predictor of severe and non-severe hail – Preliminary results from Bulgaria in 2018 – 2023

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Convective storms exist and evolve under a wide variety of conditions. As the understanding of these convective phenomena increases, so is the expectation from the people for good and accurate forecasting of these events. In Bulgaria one of the main causes of infrastructural and agricultural crops damages is related to severe weather events, such as large hail, high wind gusts and torrential rainfalls. Therefore, for the region the need for quality forecasting is essential in order to minimize the negative consequences and increase the quality of life in the region. Also there are several studies which focus on severe weather events over the region of Bulgaria, the lack of a multi-year analysis over the possibility of wind shear to be used as a predictor for hail events still remains.

This study's aim is to investigate the hail frequency, hail sizes and vertical wind shear in thunderstorms for a six-year period (2018 – 2023) over Bulgaria in order to find patterns based on the severity of the hail fall.Analysis of proximity soundings of thunderstorm events with hailfall, located in different points and calculating certain thermodynamic indices was made. A distribution of severe and non-severe hail events related to bulk shear between few different air layers and MUCAPE was examined. Hail reports were obtained by Hail suppression agency database and separated in four groups based on the diameter of the hail stones: HS1($<$ 0.5 cm), HS2(0.5-1.0 cm), HS3(1.0 – 2.0 cm) and HS4($>$ 2.0 cm). For more precise determination of the type of the cloud system a radar information from the hail suppression agency's weather radars network was used.

ThundeR – A rawinsonde package for processing convective parameters and visualizing atmospheric profiles

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ThundeR is a freeware R language package for sounding and hodograph visualization, and rapid computation of convective parameters commonly used in the research and operational prediction of severe convective storms. Core algorithm is based on C++ code seamlessly integrated into the R language within the RCPP library. This solution allows to compute a large number of thermodynamic and kinematic parameters within hundredths of a second per atmospheric profile. Such performance enables to process large numerical datasets such as reanalyses or weather prediction models for the research and operational purposes. ThundeR package has been developed since 2017 and is constantly updated with new features and parameters following requests from the community and the most up to date research findings on severe storm environments. The most recent version of the package (v1.1) allows users to calculate 201 parameters, manually specify mixing and altitude of a convective parcel, input a manual storm motion vector, and control plotting of CAPE, CIN, DCAPE and SRH polygons. An online tool available at www.rawinsonde.com allows users to use thundeR package in visualizing rawinsonde measurements and historical atmospheric profiles from ERA5 reanalysis since 1950. As of January 2023, thundeR package has been used in more than 20 peer-reviewed studies.

Radar-based hail detection and hail size estimation at DWD

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Hail is a pronounced natural hazard in Germany. Nevertheless, major hail events are quite rare and there is a lack of information in hail occurrence and size and its spatio-temporal distribution. Measurement sensors that are able to detect hail (e.g. disdrometers) are in principle available in Germany, but the spatial density of those stations is far lower than the typical spatial extent of hail events. Furthermore, sensors for hail size estimation are still in evaluation stage and currently only located at a few selected places. Hail reports based on professional and particularly amateurish eyewitness become increasingly important. But besides a certain degree of subjectivity in the reported hail size, highly populated areas might be overrepresented compared to rural and sparsely populated areas. Areal information from weather radar networks can overcome this issue with a high spatio-temporal resolution. Because of the high update frequency and fast availability of radar data, an automatic hail detection and hail size estimation might provide valuable hints to forecasters and supports the warning decision process.

The Deutscher Wetterdienst (DWD) utilizes a C-Band dual-polarimetric weather radar network consisting of 17 radar stations that provide ten volume scans and a terrain-following low-elevation scan every five minutes. The operationally used hydrometeor classification algorithm HYMEC processes data of reflectivity, differential reflectivity and co-polar correlation coefficient to distinguish between hail and other hydrometeors. With this classification a hail distribution over Germany can already be derived. For the analysis of hail sizes, the Maximum Expected Size of Hail (MESH) and a method based on Vertical Integrated Ice (VII) are used. In addition, the potential of machine learning techniques in a data-driven approach is assessed in an experimental stage.

This contribution will give an overview on the statistics of hail occurrence and hail size using the aforementioned approaches in Germany during the convective season 2022. Also, selected case studies are discussed in more detail. The results are compared against hail reports from the European Severe Weather Database and user reports from DWD's WarnWetter-App.

Deriving hail likelihood from Fengyun-4 satellite observations using an ensemble machine learning method

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Accurate estimation of the location and intensity of hail and hailstorms is still a challenge in monitoring and early warning of severe convective weather. In the past, empirical or semi-empirical methods are popularly used, which had a strong regional dependence. Satellites can provide high-resolution and continuous monitoring of atmospheric phenomena, including hail clouds, in terms of time, space, and spectral dimensions. This information can supplement the shortcomings of conventional observations and numerical forecasting models and help reduce the false alarm rate of hail and hailstorms. In this paper, a combination of the HAILCAST model and the RTTOV radiation transfer model was implemented to numerically simulate the Fengyun-4A satellite observations of five typical hail processes in China in the spring and summer of 2021 to 2023. Then, based on the simulations, principal component analysis was adopted to analyze the satellite channels and atmospheric environmental parameters corresponding to hail of different intensity sizes. Finally, a hail recognition model was constructed based on a deep learning framework. The model adopts an ensemble strategy, which integrates multiple models, including neural networks and decision tree models, into multiple layers to enhance the robustness of the model. Preliminary result shows that the accuracy of the model's predicted values compared to the true values (POD) is about 0.7. The model is also applied to a hail event in Northeast China in the spring of 2022 based on Fengyun-4A observations. The predicted results were consistent with the actual situation quite well.

Development of an omni-directional disdrometer for detection of wind-driven hail

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Wind-driven hail is a threat to the envelope of residential buildings, yet its frequency and severity remain poorly captured. The Insurance Institute for Business and Home Safety (IBHS) seeks to understand cladding vulnerability to impacts from wind-driven hailstones, and accurately testing cladding material requires an understanding of wind-driven hail impact-angle severity. In situ wind-driven hail measurements provide the opportunity to identify a typical range of impact angles during these events and increase understanding of the frequency at which hailstones fall with a non-trivial horizontal component of velocity. We aim to develop a fleet of deployable sensors capable of measuring hailstone impact angle. The sensor design includes a 6-axis force transducer surrounded by a spherical impact shell, a sonic anemometer mounted in an impact cage, and an onboard data acquisition system to process impact force and direction. The transducer is capable of measuring moments and forces separately, allowing for calculation of the force vector normal to the sphere surface and consequently the location of impact. A 4-phase proof of concept is underway to validate the instrument's capability to measure bulk impact angle and the impact angles of individual hailstones. During phase 1, the application of static force to a 5-axis force balance showed that forces in different axes can be measured separately. Phase 2 will involve mounting a hemisphere to the force balance and applying dynamic forces at pre-determined locations to verify that impact location can be derived from the axial forces. Phase 3 will involve mounting the transducer within the impact shell to test the sensor design, and Phase 4 will be the development of a fully operational prototype to be deployed in the field in 2024. These sensors will provide information about severity and frequency of wind-driven hail events and facilitate steps towards damage mitigation.

Using crowdsourced data to verify object-based nowcasting

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Since July 2020 the DWD WarnWetter-App comprises the Crowdsourcing module "User Reports". This module provides users the functionality to report observations about current weather conditions and severe weather to DWD and other users. The user reports represent the current meteorological conditions at a certain place at a certain point of time. The Crowdsourcing module provides 10 different meteorological categories (lightning, wind, hail, rain, wet icy conditions, snowfall, snow cover, cloudiness, fog, tornado), each of which contains specific characteristic levels and optionally additional attributes. In addition, the user has the option of setting the location and time of the event manually. The benefit of the data is that meteorological information at ground level is collected at places where no weather station is located in the immediate vicinity. The dataset is able to complement the existing synoptic station network. Forecasters from DWD already benefit from user-based observations that are available in near real-time.

In recent years, a new nowcasting algorithm has been developed at DWD, called KONRAD3D. The algorithm aims to automatically detect, track, and nowcast convective cells in order to support DWD's warning management. KONRAD3D uses three-dimensional radar reflectivity data as main input. In addition, also lightning data and information about hydrometeor types based on polarimetric radar data is regarded. In particular, in the latest version KONRAD3D features the new hail flag – a warning parameter that assesses a cell's threat of hail. The new parameter rests upon the hydrometeor data and should roughly estimate the expectable near-ground hail size. Other features of KONRAD3D are the gust flag – a warning parameter that estimates the maximum speed of wind gusts – and the heavy rain flag which assesses the potential of heavy rain.

This is where the crowdsourcing data comes into play. Observations from app users are able to confirm expected hail sizes on the ground and provide promptly information about wind gusts and rain intensity. Preliminary results show that KONRAD3D tends to overestimate hail and underestimate gusts and heavy rain. Our verification illustrates in which cases the warning parameter estimates were reasonable and at which point we still see room for improvement.

Identification of large hail using weather radar data in Piemonte and Emilia-Romagna regions

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It is a matter of fact that large hail occurrences have increased in the last few years in northern Italy, although the reasons have yet to be investigated. An impressive sequence of hail events characterized by large hailstones happened in the summer of 2023 when the record hail dimension was broken twice in five days: the first on 19th July in Carmignano di Brenta (PD), with a diameter of 16 cm, and the second on 24th July in Azzano Decimo (PN), reaching 19 cm diameter.

ARPAE Emilia-Romagna and ARPA Piemonte, the environmental agencies of their respective regions, have been using the output of ground hail probability algorithms based on weather radar data for many years now, and this product is useful to discriminate areas hit by hail even when there are no direct measurements. Recently they have implemented two algorithms to recognize and report the chances of large hailstones. ARPAE has implemented the VIL density method to discriminate between hail smaller and bigger or equal to 2 cm according to Amburn and Wolf (1997). The VIL density is calculated using a grid-based approach and the threshold of $3.5\,\mathrm{g\,m^{-3}}$ is applied to identify severe hail. This approach is used especially in the reports published by APRAE and ARPAP on the web and describing the meteorological events.

A radar analysis of two giant hail thunderstorms in Catalonia

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In the past two years, the most severe thunderstorms occurred in Catalonia, each associated with giant hail (> 10 cm). The first one was on 30 August 2022 and affected the North eastern part of the region. The second occurred on 26 August 2023 and reached the South of Catalonia. Such occurrences had never been previously recorded in this country and had distinct origins. However, they had points in common, such as the maritime influence or thunderstorm dimensions never recorded before them by the Catalan Weather Service. From some points of view, both thunderstorms were more likely to be tropical structures. In this study, we aim to compare the differences between themselves and between them and other thunderstorms associated with large hail (> 5 cm) recorded in the study area. This analysis has been done by considering radar techniques such as the Three Body Scatter Spike signature detection and characterization, the evolution and maximum echo top, or the Z > 55 dBZ region performance. Having in mind the limitations of the radars used in the analysis (single Pol C Band) and the location of the thunderstorms respecting the different radars, the results allow discrimination between the types of hailstorms and the probable maximum hail size, and it can help the application in real time diagnosis and nowcasting techniques.

Preliminary findings on the links between ZDR columns and hail in France

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Hailstorms are considered one of the most destructive types of storms due to the significant damage they can cause. Despite significant progress made with numerical weather prediction models and in the understanding of hail processes, forecasting thunderstorms and associated hail events remains challenging. Dual-polarization radars, which provide data at a fine temporal and spatial resolution, can highlight specific storm areas in supercells, which are particularly prone to producing severe hail (Kumjian and Ryzkhov, 2008). Regions of enhanced differential reflectivity (ZDR), with a value greater than 2 dB above the environmental freezing level, are known as ZDR columns. These columns are proxies of storm updrafts (Kumjian et al., 2014; Snyder et al., 2015). Recent studies have shown interest in ZDR columns as a potential predictor of storm severity and as an aid for the warning decision process (Kuster et al., 2019; Wilson and Van Den Broeke, 2022). This study implemented an algorithm to detect and track ZDR columns within the fully dualpolarized French radar network. The algorithm was tested on 70 convective cells of all types spread over 7 days of 2022. The storms' characteristics and their associated ZDR columns are investigated. The relationship between ZDR columns and hail occurrence is examined using hail reports from the ESWD severe weather database and a fuzzy logic hydrometeor classification algorithm (Al-Sakka et al, 2013).

The different shapes of hailstones depending on the thermodynamics

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Hailstones in Catalonia come in various shapes and sizes. Their characteristics are primarily determined by the nature of the thunderstorm and the season during which they form. Taking these factors into consideration, we have classified a large dataset of hailstones recorded from 2001 to 2021. We based our classification on various variables, including date, maximum location, and shape. All of this information was obtained from photographs of the hailstone events. The dataset has been divided into three groups based on their shapes: irregular, spherical, and embryo.

The first category encompasses all lobed and non-spherical hailstones with a diameter exceeding 1 cm. Spherical stones are those with a spherical or slightly elliptical shape, again with dimensions exceeding 1 cm. Lastly, the embryo cases refer to small hailstones not exceeding 1 cm in diameter and having a single growing layer. Additionally, sub classification has been done based on the season in which the hailstorm occurred. Through this analysis, we have observed clear differences between each group, which can be explained by thermodynamic aspects. To validate the results from the preliminary period, we have compared thermodynamic aspects of the analyzed dataset with validation cases from 2022 and 2023 campaigns, two years with extraordinary hail events in the region. We considered factors such as the number of events, the size of the stones, and the affected area.

A comprehensive description of first August 2021 hailstorm in Azzano Decimo, NE Italy

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On 1 August 2021, a vigorous hailstorm hit Azzano Decimo, in northeastern Italy. The supercell storm produced hailstones up to 10 cm in maximum dimension, which was quite unusual in this area. The storm's environment registered one of the largest potential instabilities (>3400 Jkg^{-1}) ever observed by the local operational Udine radiosonde site. The mesoscale environment supporting the storm is analyzed, with particular focus on the distribution of θ_e. Observations from the nearby operational Fossalon di Grado dual-polarization radar showed the presence of a pronounced Bounded Weak Echo Region and differential reflectivity column, both proxies for intense updrafts. However, Doppler velocities revealed only weaker winds, with the mesocyclone mostly confined to midlevels and largely absent at low levels. A comparison with the recent storm producing the new European hail size record (about 19 cm maximum dimension, which fell on 24 July 2023 also in Azzano Decimo) revealed for the latter a much lower CAPE, but a much more pronounced mesocyclone and higher Bounded Weak Echo Region.

Two independent observers in Azzano Decimo collected nine hailstones for the 1. August 2021 event, including one with a maximum dimension of 9 cm. The physical structure of these hailstones was analyzed in the National Center for Atmospheric Research (NCAR, Boulder, USA) cold room, including normal and cross-polarized light photographs of thin sections to identify the different growth layers inside each hailstone. This analysis revealed a large variability in the internal structure even if the hailstones were collected in the same location and at the same time. Additionally, ice samples were taken from 1 cm x 1 cm x 1 mm pieces from these thin slices. The analyses of the oxygen and hydrogen isotope composition were performed in Venice (Italy) on these specimens, using a Picarro cavity ring-down spectrometer. Unfortunately, the Jouzel 1975 isotopic model failed to relate the isotopic composition to specific cloud temperatures (estimated from adiabatic analysis), because of the large variability present in the isotopic data of the hailstone samples.

Evolution of severe hailstorms as observed by polarimetric X-band radar at the Milešovka observatory

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Two events with severe hail occurring in the range of the Milešovka X-band radar are analysed. During the radar operation period since 2020, only those two days with severe hail reports and radar detection were found.

On 27 June 2022 storms formed during the afternoon hours over a spacious part of Czechia in the warm air ahead of a cold front. Severe hail was recorded in many places over the Czech territory. Hail was also reported from the foothills of the Ore Mountains and south of the Bohemian Central Highlands within the range of Milešovka X-band radar. On 30 July 2023 supercell storm evolved near Louny town and moved westward along the Ohře river valley and further along the Elbe valley. Severe hail was reported from several places near Roudnice nad Labem. The events are analyzed with dual-polarized Doppler weather radar FURUNO, which is located at the top of the Milešovka observatory tower. The scanning strategy includes both PPI and RHI scans in one cycle lasting 170 s and allows a detailed description of the storm structure. The evolution of the reflectivity field, differential reflectivity and other quantities is investigated. Also the data from Czech weather service C-band radars are used for comparison. In addition the lightning activity related to hail development in storms is examined.

Comparative study into the melting of spherical and natural-like hailstones

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We will present our experimental studies in which we compared the melting behavior of hailstones with spherical and natural-like shapes. The experiments were carried out in the Mainz wind tunnel which ensured the investigation of the most important factors such as fall speed, shape, meltwater content, and the shed droplet size distribution of melting particles when freely floating in a vertical air stream. The shape variation from the fully glaciated to the completely molten state was observed by means of a video camera, while the drop size distribution of the shed droplets was measured by an in-house built digital holographic instrument. The advantage of the holographic technique is the capability to obtain the correct size information of the droplets, independent from their distance from the hailstone and the position within the wind tunnel. The experiments were performed applying dry and moist adiabatic temperature gradient and at different relative humidities from about 0 to 80 %. Our measurements provide insight into the shape and fall speed variation during melting, and the formation mechanism of a bimodal size distribution of droplets shedding off the hail particles.

A wind tunnel investigation on the heat and mass transfer of hailstones

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The accuracy of weather forecast models to predict precipitation depends strongly on the representation of cloud processes in those models. Recently, it was demonstrated that the development and life time of a convective storm is critically dependent on the representation of heat and mass transfer coefficients of the ice particles, implying that small scale processes are able to affect storm dynamics. Therefore, it is important to understand the underlying physics in order to implement those in forecast models. Parameters such as the heat and mass transfer coefficients are among others crucial for simulating the growth or dissipation of hailstones but are still not well represented in forecast models.

The rate of change of mass of a falling hailstone in the convective-diffusive growth mode is affected by their fall velocity leading to an enhanced mass and heat transport compared to a pure diffusive case. This convective enhancement can be characterized by the Sherwood number.

Here we present results of experiments carried out in the Mainz vertical wind tunnel from which Sherwood numbers of spherical and natural hailstones in the convective-diffusive growth mode were obtained. We investigated stones of diameters between 1 and 4 cm or equivalently with Reynolds numbers between 10’000 and 30’000. The hailstones were produced by freezing water in molds and introduced into the wind tunnel. In order to prevent the stones from collisions with the wind tunnel walls they were captively floated at different wind speeds. Exposed to sub-saturated air the hailstones lost mass by sublimation. From the measured masses before and after the measurement the rates of change of mass in the convective-diffusive case were derived. The recordings of temperature and dew point were used to calculate the rate of change of mass for pure diffusion in case of the spherical hailstones. The one for natural hailstones was either measured in a diffusion chamber or calculated based ion its capacitance. From both rates the Sherwood numbers were calculated and parameterized. These can be used directly to calculate the evolution of hailstones as they grow and fallout.

Analysis of insoluble particles in hailstones in China

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Insoluble particles influence weather and climate by means of heterogeneous freezing process. Current weather and climate models face considerable uncertainties in freezing-process simulation due to limited information regarding species and number concentrations of heterogeneous ice-nucleating particles, particularly insoluble particles. Here, for the first time, the size distribution and species of insoluble particles are analyzed in 30 shells of 12 hailstones collected from China using scanning electron microscopy and energy-dispersive X-ray spectrometry. A total of 289’461 insoluble particles were detected and divided into three species – organics, dust, and bioprotein – utilizing machine learning methods. The size distribution of the insoluble particles of each species varies greatly among the different hailstones but little in their shells. Further, a classic size distribution of organics and dust followed logarithmic normal distributions, which could potentially be adapted in future weather and climate models despite the existence of uncertainties. Our findings highlight the need for atmospheric chemistry to be considered in the simulation of ice-freezing processes.

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