Workshop 'Clouds containing Ice Particles'
Joh. Gutenberg Univ. Mainz, 'Alte Mensa', 23 - 26 July, 2023

Organizing Committee:

Martina Krämer (Research Center Jülich, JGU Mainz), Greg McFarquhar (Univ. Oklahoma)
Peter Spichtinger (JGU Mainz), Philipp Reutter (JGU Mainz)

Location:

(https://www.mainz-tourismus.com/en/ https://upload.wikimedia.org/wikipedia/commons/d/d4/Uni_Mainz_-_Alte_Mensa_2.jpg)

Funding Organizations:

Gutenberg Research College, JGU Mainz
(GRC: https://www.grc.uni-mainz.de/)

Institute for Atmospheric Physics, JGU Mainz
(IPA: https://www.blogs.uni-mainz.de/fb08-ipa-en/arbeitsgruppen/)

International Commission for Clouds and Precipitation
(ICCP: https://www.iamas.org/iccp/members/)

The intention of the workshop is to discuss all aspects of cirrus and mixed-phased clouds - the least understood cloud types, but contributing significantly to the uncertainty in climate predictions.The topics of the workshop are intended to be comprehensive, from in-situ and remote sensing observations of clouds to their modeling on all scales. We have contributions on the state of knowledge, new findings and open questions, as well as on experimental, theoretical and computational methods used in research.

Catering: Monday - dinner, Mon-Wed - coffee + cookies, lunch snack.

The workshop has 75 participants from 11 countries and 32 instutions

Workshop website
https://www.ipa.uni-mainz.de/clouds-containig-ice-particles/

We are looking forward to seeing all participants very soon !

And we thank the GRC, the ICCP
and all helpers from the IPA for the opportunity to organize this workshop.

Martina, Greg, Philipp and Peter

Mainz, 5th July 2023

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Workshop 'Clouds containing Ice Particles'

Joh. Gutenberg Univ. Mainz, 'Alte Mensa', 23 - 26 July, 2023

Programm

		Morning			Lunch	Afternoon			Evening
24. July	**Mon.**		10-11 Welcome	11-12 **CI** in-situ Eric Jensen	12-14 Poster **1** teasers	14-15 **CI** rem.sens. Odran Sourdeval	15-16 Poster **1**	16-17 **CI** sim. Blaž Gasparini	18:30 Barbeque
25. July	**Tue.**	9-10 **CI** sim. Klaus Gierens	10-11 Poster **2** teasers	11-12 **Lab. Studies** Miklós Szákall	12-13 Lunch	13-14 **MPC** in-situ Greg McFarquhar	14-16 Poster **2**	16 Cloud channel tour	Cloud channel tour
26. July	**Wed.**	9-10 **MPC** sim. Anna Jaruga	10-11:15 Poster **3** teasers	11:15 -12 **INP** Luisa Ickes	12-14 Poster **3** Lunch	14-15 **Ice** mult. Alexei Kiselev	15-16 Closing		

CI in-situ: Cirrus clouds: in-situ measurements, **CI** rem.sens.: Cirrus clouds: remote sensing observations, **CI** sim.: Cirrus clouds: theory and simulations,
MPC in-situ: Mixed phase clouds: in-situ measurements, **MPC** sim.: Mixed phase clouds: theory and simulations,
INP: Ice nucleating particles, **Ice** mult.: Ice multiplication processes, **Lab.** Studies: Laboratory studies (Mainz cloud channel)

July 25, 2023

Poster Session 1	Monday	24 July
Andrew Dzambo	Ci-ins	1.1.7
Elena de la Torre Castro	Ci-ins	1.1.5
Athulya Saiprakash	Ci-rem	1.2.2
David Mitchell	Ci-rem	1.2.8
Peter Spichtinger	Ci-sim	1.3.4
Stamen Dolaptchiev	Ci-sim	1.3.6
Dario Sperber	Ci-sim	1.3.8
Aurelien Podglajen	Ci-sim	1.3.13
Anthony Baran	Ci-sim	1.3.15
Christopher Hohman	MPC-ins	2.1.7
Johanna Mayer	MPC-rem	2.2.3
Barbara Dietel	MPC-rem	2.2.4
Alberto De Lozar	MPC-sim	2.3.5
Christoph Siewert	MPC-sim	2.3.6
Diego Villanueva	MPC-sim	2.3.9
Britta Schäfer	MPC-sim	2.3.11
Christof Beer	INP	4.2
Cuiqi Zhang	INP	4.6
Florian Reyzek	INP	4.7
Veronika Ettrichraetz	Instr.	5.1

Poster number - corresponds to the number in the Book of Abstracts (page 5ff)

Poster format is A0

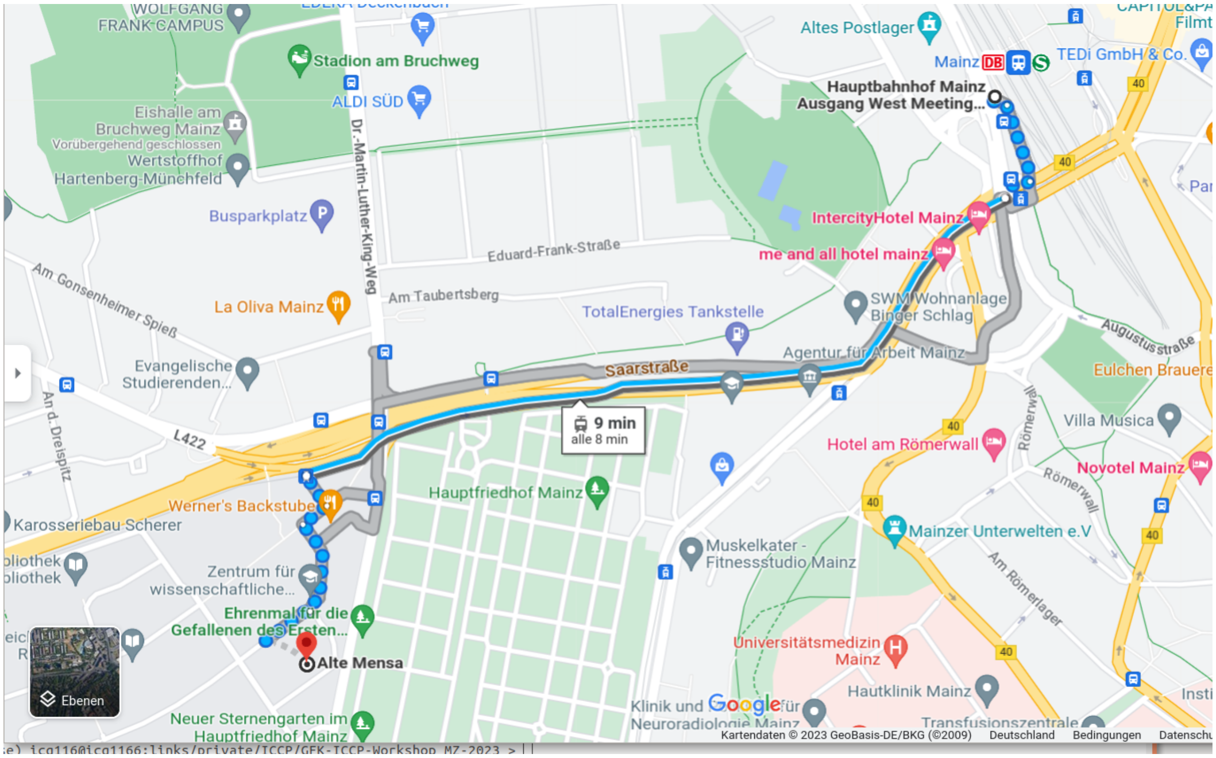
Poster Session 2	Tuesday	25 July
Martina Krämer	Ci-ins	1.1.2
Nils Brast	Ci-ins	1.1.4
Johannes Röttenbacher	Ci-rem	1.2.3
Georgios Dekoutsidis	Ci-rem	1.2.5
Kai Jeggle	Ci-rem	1.2.7
Blaz Gasparini	Ci-sim	1.3.3
Hannah Bergner	Ci-sim	1.3.5
Alena Kosareva	Ci-sim	1.3.7
Karol Corko	Ci-sim	1.3.10
Jhaswantsing Purseed	Ci-sim	1.3.12
Jan Henneberger	MPC-ins	2.1.3
Jeffrey R. French	MPC-ins	2.1.6
Leonie von Terzi	MPC-rem	2.2.1
Tim Lüttmer	MPC-sim	2.3.3
Gabriella Wallentin	MPC-sim	2.3.7
Huiying Zhang	MPC-sim	2.3.10
Luisa Ickes	MPC-sim	2.3.12
Polly Foster	INP	4.4
Erin Raif	INP	4.5
Janos Stenszky	Instr.	5.2

Poster Session 3	Wednesday	26 July
Yun Li	Ci-ins	1.1.3
Rachel Atlas	Ci-ins	1.1.6
Silke Gross	Ci-rem	1.2.4
Anthony Baran	Ci-rem	1.2.6
Ulrike Burkhardt	Ci-sim	1.3.9
Simon Unterstrasser	Ci-sim	1.3.11
Tuule Müürsepp	Ci-sim	1.3.14
Edgardo Sepulveda Araya	Ci-sim	1.3.16
Samantha Turbeville	Ci-sim	1.3.17
Simon Kirschler	MPC-ins	2.1.4
Nina Maherndl	MPC-ins	2.1.5
Anna Weber	MPC-rem	2.2.2
Roland Schrödner	MPC-sim	2.3.8
Theresa Kiszler	MPC-sim	2.3.4
Ong Chia Rui	MPC-sim	2.3.14
Sachin Patade	SIP	3.2
Zane Dedekind	SIP	3.3
Mark D. Tarn	INP	4.3
Sylwester Arabas	INP	4.8
Saurabh Patil	Instr.	5.3
Samantha Clarke	MPC-ins	2.1.8

Workshop Location:

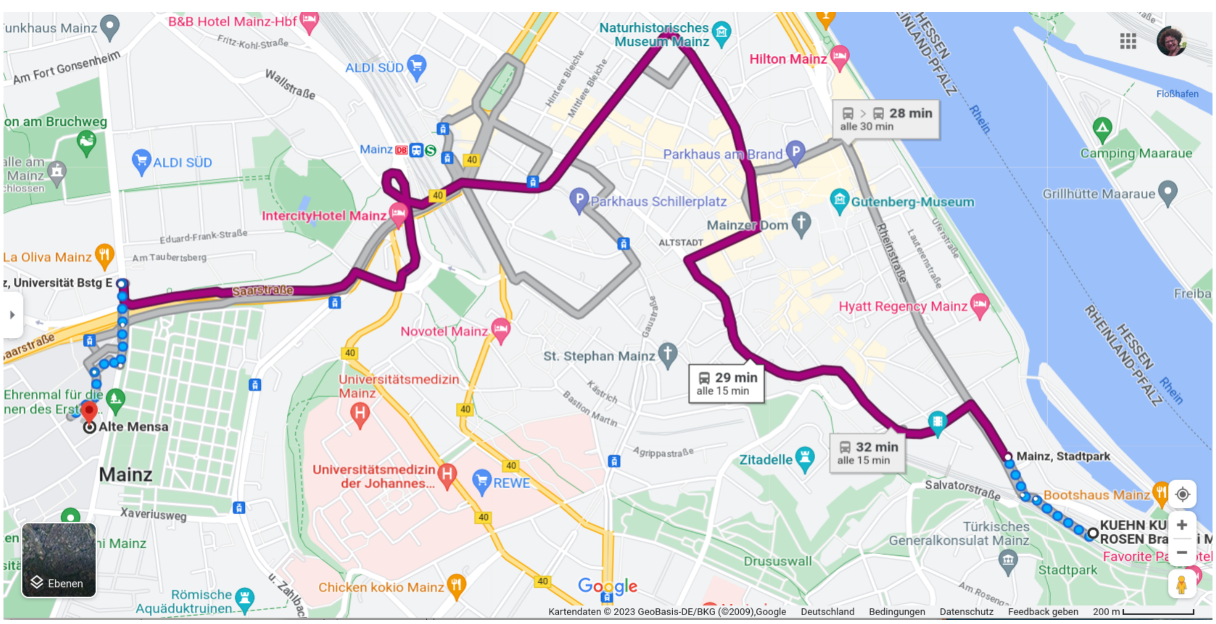
Address of the ’Alte Mensa’, Campus JGU Mainz:
Johann-Joachim-Becher-Weg 3, 55128 Mainz

Route from Mainz main station to ’Alte Mensa’



Location of the workshop dinner on Monday 24 July, 7pm:

Kuehn Kunz Rosen Brauerei, Weisenauer Str. 15, 55131 Mainz
www.kuehnkunzrosen.de



Book of Abstracts

Workshop
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1 Cirrus clouds

1.1 In-situ measurements

1.1.1 Eric Jensen (invited)

NOAA Chemical Sciences Laboratory/CIRES, Boulder, USA

What have we learned from in situ measurements of cirrus: physical properties and processes

In this presentation, I will review the in situ measurements of cirrus made over the last two decades. I will discuss the ice crystal physical properties that can only be obtained by in situ measurements, such as size distribution and habit. I will also discuss what we have learned from in situ measurements about cirrus physical processes, such as ice nucleation, deposition growth, aggregation, and interaction with waves. An emphasis of the presentation will be recent in situ measurements in cirrus generated by deep convection at different stages in the anvil lifecycle. In particular, measurements in active convection show broad ice crystal size distributions with abundant small (D ¡ 20 um) ice crystals as well as large aggregates. Measurements slightly downstream of the convection show that the small crystals disappear rapidly, and bullet rosettes tend to quickly dominate the crystal habits. I will discuss the possibility that interaction with convectively-generated gravity waves can explain this transition in cirrus properties.

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1.1.2 Martina Krämer

Martina Krämer[1,2], Nicole Spelten[1], Armin Afchine[1] and Reinhold Spang[1]

[1] Forschungszentrum Jülich, IEK-7 Stratosphere, Jülich, Germany
[2] Johannes Gutenberg-Universität Mainz, IPA, Mainz, Germany

Occurrence patterns of cloud particles sizes in cirrus and mixed-phase clouds

The sizes and number of cloud particles are crucial parameters that determine the physical and optical properties of clouds and with that their radiative feedback to climate. However, measurements of cloud particle size distributions (PSDs) are difficult to accomplish, because clouds are always located at a certain height in the atmosphere. In addition, the entire cloud particle size range cannot be covered with one instrument and also, an undisturbed sampling cloud particles across their entire size range has only been successful for about 15 years.
To build a larger data set of cloud PSDs, we have merged PSD measurements from 11 airborne field campaigns between 2008 and 2021 in tropical, mid-latitude and Arctic ice, mixed and liquid clouds, where we spend a total of 238 hours of measurement time in clouds during 163 flights, of which 131 hours in ice clouds, 62 hours in mixed clouds and 45 hours in liquid clouds. The cloud PSDs are from different instruments which do not record particle sizes in equally sized intervals. Therefore, the cloud particle numbers are interpolated to a logarithmic equidistant size grid. From this synchronized data set it is now possible to derive not only averaged PSDs, but occurrence frequencies of particle sizes and numbers. We here present occurrence patterns of particle sizes and concentrations in mixed-phase and cirrus clouds in 10°C temperature intervals between -90 to 0°C.
In this study we analyse cirrus clouds in more detail by sorting the PSDs in three ranges of ice water content and temperatures, respectively. First results show that in thin cirrus - which are mostly of in-situ origin- the dominant ice particle size changes from small ice particles at low temperatures (∼3-20 µm diameter) tolarger sizesin warmercirrus (∼20 µm diameter) to larger sizes in warmer cirrus (∼20–200 µm diameter) tolargersizesinwarmer cirrus (∼20 µm). Thick cirrus, which are a mixture of in-situ and liquid origin, generally contain larger ice particles at all temperatures, the warmer the temperature, the larger ice particles appear in the PSDs.
These occurrence pattern represent a valuable data set that can be used to validate and improve the representation of especially ice clouds in global climate models and in the retrieval of satelllite-based remote sensing observations.

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1.1.3 Yun Li

Yun Li[1,2], Christoph Mahnke[1], Susanne Rohs[1], Ulrich Bundke[1], Nicole Spelten[2], Georgios Dekoutsidis[3], Silke Groß[3], Christiane Voigt[3,4], Ulrich Schumann[3], Andreas Petzold[1] and Martina Krämer[2,4]

[1] Forschungszentrum Jülich, IEK-8 Troposphere, Jülich, Germany
[2] Forschungszentrum Jülich, IEK-7 Stratosphere, Jülich, Germany
[3] Deutsches Zentrum für Luft- und Raumfahrt, IPA, Oberpfaffenhofen, Germany
[4] Johannes Gutenberg-Universität Mainz, IPA, Mainz, Germany

Observational evidence of contrail cirrus in slightly ice-subsaturation

Contrail cirrus, including line-shaped contrails, has a net warming effect on the Earth's climate. Of great importance to estimate their radiative effect is the coverage and mean optical thickness, which are closely associated with the conditions affecting the formation and microphysical properties of contrail cirrus.

This study focuses on cirrus observations over central Europe and the Northeast Atlantic from the airborne ML-CIRRUS campaign in 2014. Contrail cirrus in the cirrus dataset is identified using: (1) the Schmidt-Appleman-Criterion, which determines whether the environmental conditions are suitable for contrail formation, (2) an aircraft plume detection algorithm that helps identify if a measured air mass originated from aircraft exhaust, and (3) statistical analysis that generates a description of the general characteristics of contrail and natural cirrus.

The microphysical properties (mass mean radius R_{ice}, ice crystal number N_{ice} and ice water content IWC) of contrail cirrus and natural cirrus will be described in this work together with their occurrence conditions. The preferred atmospheric conditions of contrail cirrus occurrence are identified. Of particular interest is the existence of contrail cirrus in slightly ice-subsaturated environments, where the relative humidity with respect to ice (RH_{ice}) centres around 90 % instead of ice supersaturation, as believed hitherto. This also differs from 100 % RH_{ice} in natural cirrus. Inspecting the occurrence frequencies of air masses with $RH_{ice} > 90$ % compared to $RH_{ice} > 100$ % from passenger aircraft observations above Europe and the North Atlantic during the IAGOS-MOZAIC period from 1995 to 2010, about 43 % of the air masses are prone to contrail cirrus formation instead of 32 % found in ice-supersaturated environments. Our findings imply that the avoidance of slight ice-subsaturation to ice-supersaturation at cruising altitudes might further reduce the occurrence of contrail cirrus, thus diminishing the climate impact of contrail cirrus.

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1.1.4 Nils Brast

Johannes-Gutenberg University, Mainz, Germany

3D climatology of ice supersaturated regions over the North Atlantic

Water vapor is an essential component for regulating the Earth's radiation budget. To realistically determine the global radiation budget, an accurate description of the water vapor distribution in the upper troposphere and lower stratosphere (UTLS) is therefore indispensable. For example, small changes in water vapor concentration can lead to significant changes in local radiative forcing, especially in the dry lower stratosphere. The change in this region can be even stronger if condensed water in the form of ice clouds is present instead of solely water vapor.

The formation and evolution of ice clouds is crucially determined by the saturation ratio over ice (Si). Ice crystals can only form (and grow) at supersaturated conditions (i.e. $Si > 1$), i.e. in so-called ice supersaturated regions (ISSRs), which also constitute potential regions for the formation and existence of persistent aircraft contrails. Knowing and precisely forecasting the occurrence of ISSRs can help reducing the contribution of aviation to man-made climate change, as contrails usually have a warming effect on the climate.

Ice supersaturation is often observed in the UTLS. However, despite their importance, the large-scale three-dimensional structure of ISSRs is widely unknown. Therefore, we present a three-dimensional climatology of ice supersaturation in the UTLS over the North Atlantic for the years 2010 to 2019. This climatology is based on the recent ERA5 reanalysis data set of the European Center for Medium Weather Forecast (ECMWF), which explicitly allows ice supersaturation in cloud-free conditions. To quantify the quality of the ERA5 data set with respect to ice supersaturation, we use the long-term in-situ measurements of the European Research Infrastructure 'In-service Aircraft for a Global Observing System' (IAGOS; www.iagos.org) (Petzold et al., 2015).

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1.1.5 Elena de la Torre Castro

Deutsches Zentrum für Luft- und Raumfahrt (DLR) Oberpfaffenhofen, Oberpfaffenhofen, Germany

Differences in microphysical properties of cirrus at high and mid-latitudes

Cirrus in mid latitudes (<= 60° N) are often affected by aviation and pollution while cirrus in high latitudes (> 60° N) develop in a more pristine atmosphere. In this study, we compare the microphysical properties of cirrus measured in mid latitudes and cirrus measured in high latitudes. The analyzed properties are: the ice crystal number concentration (N), effective diameter (ED) and ice water content (IWC) of cirrus from in situ measurements during the CIRRUS-HL campaign in June and July 2021. We use a combination of cloud probes covering ice crystals sizes between 2 and 6400 µm. The differences in cirrus properties are investigated with dependence on altitude and latitude and we show that there exist differences between mid-latitude and high-latitude cirrus. An increase in ED and a reduction in N is observed in high-latitude cirrus compared to mid-latitude cirrus.

In order to investigate the cirrus properties in relation to the region of formation, we also combine our measurements with 10-day backward trajectories to identify the location of cirrus formation and the cirrus type: in situ or liquid origin cirrus. According to the latitude of cloud formation and latitude of the measurement, we classify the cirrus in three groups: cirrus formed and measured at mid latitudes (M-M), cirrus formed at mid latitudes and measured at high latitudes (M-H) and cirrus formed and measured at high latitudes (H-H). This analysis shows that part of the cirrus measured at high latitudes are actually formed at mid latitudes and therefore influenced by mid-latitude air masses. We discuss the differences of the cirrus properties under this new classification. Our study helps to advance the understanding of upper-tropospheric cirrus properties at mid and high latitudes in summer and the influence of anthropogenic perturbations.

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1.1.6 Rachel Atlas

Rachel Atlas, Thomas Lesigne, Aurélien Podglajen

IPSL Dynamic Meteorology Laboratory (LMD), Guyancourt, France

Detecting gravity waves and turbulence within airborne lidar images of cirrus clouds in the tropical troposphere layer

NASA's cloud physics lidar (CPL) profiled tropical tropopause layer (TTL) cirrus clouds during the multi-year ATTREX aircraft campaign, collecting a total of 90 hours/65 km of high resolution ($\sim$ 200 m horizontal, 30 m vertical) imagery over the Pacific Ocean. Gravity wave activity and turbulence are detectable by eye within the lidar imagery. We apply image processing and frequency analysis techniques to automatically detect different types of small-scale dynamics within 1064 nm backscatter profiles measured by the CPL. We derive nearest neighbour atmospheric parameters from ERA5 reanalysis to correlate TTL cirrus occurrence and microphysical properties with wave-induced temperature and wind anomalies within ERA5.

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1.1.7 Andrew Dzambo

Andrew Dzambo, Greg McFarquhar, Chip Helms and Lee Thornhill

University of Oklahoma (OU), Norman, Oklahoma

Synergizing in-situ cloud probe measurements and radar reflectivity curtains for diagnosing in-cloud turbulence and gravity wave activity

Turbulence and gravity waves are two atmospheric processes that affect the evolution of cloud and precipitation properties. Remote sensing and in-situ airborne probes offer unique advantages for observations of cloud and precipitation properties (e.g., ice water content or IWC, number concentration, ice particle habit), but each alone has limitations. It is the synergy of the two measurement techniques that best allows information about processes acting in clouds to be hypothesized. Using data from the High Altitude Ice Crystals – High Ice Water Content (HAIC-HIWC) and Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS) projects, in-situ measurements of ice water content, etc., 3-D wind measurements from the Turbulence Air Motion Measurement System, and an adapted wavelet technique are used to diagnose regions of turbulence and gravity waves.
Similarly, the wavelet technique is applied to transects of X-band Radar Doppler velocity data to diagnose such regions, with comparison against the in-situ derived regions showing the degree of consistency between the techniques. The wavelet technique is shown to resolve turbulence from scales of $\sim$ 10 to 200 meters for 15-min flight legs, and gravity waves on the order of 5-20 km. In regions of statistically significant turbulence activity, local maxima of IWC are more likely to occur. Additionally, case studies showing flight legs that intersect ice-precipitating clouds at various altitudes (top of the cloud, below cloud base, etc.) are highlighted in the context of present turbulence and gravity wave conditions.

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1.2 Remote sensing observations

1.2.1 Odran Sourdeval (invited)

University of Lille, Lille, France

Understanding ice clouds from satellite observations

Understanding and characterizing ice clouds from satellite observations presents significant challenges, largely due to their inherent variability and to the complexity of their micro- and macro-physical properties. Primary among these challenges is the accurate representation of these properties in retrieval algorithms, encompassing variables such as the particle size distribution, the mass-dimension relationship, as well as the shape and multiple habits of ice crystals. The consistency between microphysical and optical cloud properties is indeed a crucial step towards robust cloud retrievals. Another prominent difficulty is the variable sensitivity of satellite instruments to different types of ice clouds, with particular issues arising when detecting very thin cirrus clouds.

This presentation takes an in-depth look at the practices in satellite remote sensing techniques for cirrus clouds, offering a thorough analysis of current capabilities while pinpointing existing challenges. As part of our discussion, we will investigate the latest advancements in the domain, with a particular focus on lidar-radar techniques. Furthermore, we will overview recent efforts to align satellite-based observations with in-situ measurements and model outputs, emphasizing the value of consistency between these different approaches. To conclude, we will introduce upcoming satellite missions aiming at improving our understanding of ice clouds.

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1.2.2 Athulya Saiprakash

A. Saiprakash[1], P. Konjari[2], G. Horner[3], C. Rolf[2], M. Krämer[2,4], and O. Sourdeval[1]

[1] Laboratoire d'Optique Atmosphérique, Université de Lille, Lille, France
[2] Forschungszentrum Jülich GmbH, IEK-7, Jülich, Germany
[3] Space and Atmospheric Physics Group, Imperial College London, London, UK
[4] Institute for Atmospheric Physics (IPA), Johannes Gutenberg University, Mainz, Germany

Investigating ice cloud formation mechanisms from satellite observations and Lagrangian transport and microphysical models

Ice clouds are challenging because of the high complexity and diversity of their composition (microphysics) as well as formation and growth processes. As a result, there has been little constraint from observations until recently, resulting in significant limitations in our understanding and representation of ice clouds. A major problem with satellite measurements is the lack of information on the environmental context, which is necessary to identify and understand formation mechanism and evolution of cloud; these renditions indeed only represent a snapshot of the state of a cloud and its microphysical properties at a given time. This work tackles this issue by providing additional metrics on ice cloud history and origin along with operational satellite products.

Here, we present a novel framework that combines satellite observations with Lagrangian transport and ice microphysical models, in order to obtain information on the history and origin of air parcels that contributed to their formation. The trajectory of air parcels encountered along the DARDAR-Nice track has been traced using the air mass transport models CLaMS (Chemical LAgrangian Model of the Stratosphere). CLaMS - Ice model is jointly used to simulate cirrus clouds along trajectories derived by CLaMS. This approach provides information on the cloud regime as well as ice formation (in-situ vs liquid origin) pathway. For tropical cirrus of convective origin, a Time Since Convection dataset from geostationary observations can also be incorporated in this approach. Preliminary results of this approach obtained on case studies representative of multiple cloud types will be shown here.

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1.2.3 Johannes Röttenbacher

Johannes Röttenbacher[1], Hanno Müller[1], André Ehrlich[1], Florian Ewald[2], Michael Schäfer[1], Anna Luebke[1], Benjamin Kirbus[1], Martin Wirth[2], Manfred Wendisch[1]

[1] Leipzig Institute for Meteorology, Leipzig University, Leipzig, Germany
[2] German Aerospace Center (DLR), Institute of Atmospheric Physics, Oberpfaffenhofen, Germany

Quantification of the Radiative Effect of Arctic Cirrus by Airborne Measurements - A Case Study

Remote sensing observations of cirrus in the central Arctic over sea ice (81°-90° North) were obtained within the HALO – $(AC)^3$ aircraft campaign in March and April 2022. The High Altitude LOng range research aircraft (HALO) operated by the German Aerospace Center (DLR) was equipped with its remote sensing cloud observatory configuration including among other instruments a radar, a lidar and broadband irradiance sensors providing a detailed characterization of the single layer isolated cirrus.

Flight legs above and below the cirrus with measurements of solar and terrestrial irradiance are used to estimate the cloud radiative effect. The cirrus was sufficiently thick to reduce the transmission of solar radiation by around 25%. However, significant inhomogeneities in the cirrus were observed.

For this case study the measured radiative effect of Arctic cirrus is compare to simulations of the ECMWF's Integrated Forecasting System (IFS) making use of offline runs of the operationally used ecRad radiation scheme.

Additional simulations use cloud properties of the VarCloud retrieval from Ewald et al. 2021 to replace the IFS ice effective radius and ice water content. The VarCloud data significantly reduced the bias between the simulation and measurement from -20 Wm^{-2} to -8 Wm^{-2}. This improvement mostly results from the larger ice effective radii retrieved by VarCloud than are predicted by the IFS parameterization.

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1.2.4 Silke Gross

Silke Gross[1], Qiang Li[1], Martin Wirth[1], Tina Jurkat-Witschas[1], Martina Krämer[2,3], Christiane Voigt[1,3]

[1] Deutsches Zentrum fuer Luft- und Raumfahrt (DLR) e.V., Insitute for Atmospheric Physics, Germany
[2] Forschungszentrum Jülich, Institut für Energie- und Klimaforschung, Germany
[3] Johannes-Gutenberg-Universität, Mainz, Germany

Investigating an aviation induced indirect aerosol effect on cirrus clouds using airborne and spaceborne lidar measurement

Emissions from aviation have a large effect on the Earth's radiation budget and impact the Earth's atmosphere by a combination of different processes. E.g. line shaped contrails can form in the exhaust plume of an aircraft and might evolve into contrail induced cirrus clouds in the aftermath. Those contrails and contrail induced cirrus clouds are supposed to have the largest aviation induced impact on the Earth's radiation budget with a clearly warming effect. Furthermore, aviation induced aerosols might change the micro-physical and thus optical properties of naturally formed cirrus clouds. Model studies investigating the impact of this aerosol-cloud interaction show large differences in the resulting effective radiative forcing.

Measurements with our polarization sensitive airborne high spectral resolution lidar system performed over the European mid-latitudes show differences in the measured particle depolarization ratio of cirrus clouds formed in rather pristine regions and those formed in regions with enhanced background aerosol due to air traffic exhaust. For the first time we could thus show an indication of an aviation induced indirect aerosol effect on naturally formed cirrus clouds. But, high resolution airborne measurements are limited in time. During the past years civil aviation over Europe showed a large increase with respect to flight density. Long-term satellite lidar observations (CALIPSO) are used to investigate if this increase in civil aviation has also an effect on cirrus cloud properties. We find a trend in the measured particle linear depolarization ratio of cirrus clouds over Europe over the past ten years that might be related to changes in civil aviation. Additionally, in spring 2020 air traffic over the European mid-latitudes was reduced by about 80% due to the COVID-19 pandemic. This reduction offered a unique opportunity to study cirrus clouds in a situation less affected by aviation.

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1.2.5 Georgios Dekoutsidis

G. Dekoutsidis[1], S. Groß[1], M. Wirth[1]

Institut für Physik der Atmosphäre, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Oberpfaffenhofen, Germany

The effects of warm air intrusions in the high arctic on cirrus clouds

In the last decades scientist have noticed that the average global temperature of the Earth has been increasing. Moreover, the arctic is warming significantly faster than the global average, a phenomenon labeled Arctic Amplification. Warm air intrusions (WAI) are events during which warm and water-vapor-rich airmasses are transported from the mid-latitudes into the otherwise cold and dry arctic. Cirrus clouds that form during these events are expected to have different formation processes and characteristics. Since these events are expected to have a positive trend in frequency and duration it is important to study how they affect the arctic and the cirrus that form there.

The HALO-(AC)3 flight campaign was conducted in March/April 2022 aiming, among others, to study WAI events. For this campaign the German research aircraft HALO was equipped with remote sensing instrumentation, including the airborne LIDAR system WALES, which is a combined water vapor differential absorption and high spectral resolution lidar. It provides water vapor measurements in a 2D field along the flight track.

In our study, we analyze each flight and distinguish between two types of cirrus clouds: The first category are clouds measured under undisturbed arctic conditions (AC cirrus) and the second are cirrus measured during a prevailing WAI event (WAI cirrus). Then, we combine the WALES water vapor measurements with ECMWF temperature data and calculate the Relative Humidity over ice (RHi) inside and in the vicinity of these two cloud groups.

From our study we confirm that the arctic atmosphere is warmer and contains more water vapor during a WAI event. Additionally, we find that WAI cirrus are geometrically thicker, which leads to them being detected in a wider temperature range. They are also more frequently supersaturated. Inside AC cirrus high supersaturations over the threshold for homogeneous nucleation are rarely detected, contrary to WAI cirrus.

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1.2.6 Anthony Baran

Anthony J. Baran[1,2], Andrew J. Heymsfield[3], Antigoni Kleanthous[4], Christopher Westbrook[5], Timo Betcke[4], and David P. Hewett[4], and Paul Barrett[1]

[1] Met Office, U. K.
[2] University of Hertfordshire, U. K.
[3] National Centre for Atmospheric Research, U.S.A.
[4] University College London, U. K.
[5] University of Reading

Testing Model Consistency using the Boundary Element Method for Computing Backscattering Properties of Complex Ice Crystals at Multiple Frequencies Using Radar Reflectivity Data from the IMPACTS Campaign

The backscattering properties of randomly oriented complex rosette ice aggregates at the radar frequencies of 9, 35, and 94 GHz are computed using the boundary element method. A Monte Carlo model is used to generate rosette aggregates, and 65 aggregates are selected from statistical runs that are within ±30% of a mass–dimension relation consistent with the Met Office's cirrus microphysics scheme in its weather and climate models. The area–dimension relationship of the rosette aggregate model is shown to be generally consistent with in-situ observations of the area–size power law. The aggregates have maximum dimensions between 10 µm and approximately 1 cm. To test the rosette aggregate model and another commonly used model in the microwave, data from NASA's Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms campaign (IMPACTS) is used. The IMPACTS data consists of four frontal snowstorm cases that achieved the best co-incident measurements between the in-situ and remote-sensing aircraft. The rosette aggregate model predicts the time series of radar reflectivity observations generally very well from all four cases. Although there are a few regions in the time series of radar observations that are not well simulated by either model, the rosette aggregate model appears suitable to apply across the microwave spectrum. The poster will also provide details of the location of the rosette aggregate microwave database that is currently under construction.

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1.2.7 Kai Jeggle

Eidgenössische Technische Hochschule (ETH) Zürich, Zürich, Switzerland

Identification of cirrus formation regimes using cluster analysis of back trajectories and satellite data

In recent years our understanding of cirrus cloud processes has been significantly advanced. However, a large uncertainty regarding the influence of cirrus formation mechanisms on the microphysical properties, and hence radiative properties of cirrus clouds still remains. This leads to uncertainty in global climate models and climate change projections. In this work we aim to identify different cirrus formation regimes and analyze their influence on cirrus microphysical properties. We combine DARDAR-Nice satellite observations with Lagrangian back trajectories of meteorological and aerosol reanalysis data on the Northern Hemisphere. Our goal is to classify observed cirrus clouds by means of their trajectories and investigate the trajectories' influence on observed cirrus microphysical properties. With our data-driven nested clustering approach we identify different meteorological regimes that lead to cirrus formation. We are also able to isolate the effect of dust ice nucleating particle (INP) exposure along the trajectory from meteorological variability.
We identify four different meteorological clusters that lead to characteristic cirrus cloud microphysical properties and can be associated with liquid origin and in-situ formed cirrus clouds. Furthermore, we find that dust concentrations in cirrus cloud back trajectories are significantly higher compared to cloud free trajectories with comparable meteorological conditions. This indicates the importance of dust acting as INP during heterogeneous nucleation. The magnitude of the dust concentration, however, has only a negligible effect on cirrus microphysical properties.

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1.2.8 David Mitchell

David Mitchell[1] and Anne Garnier[2]

[1] Desert Research Institute, Reno, Nevada, USA
[2] Science Systems and Applications Inc., Hampton, Virginia, USA

Global Estimates of the Fraction of Cirrus Clouds affected by Homogeneous Ice Nucleation

Following Mitchell et al. (ACP, 2018), an improved CALIPSO satellite retrieval for cirrus clouds has been developed for number concentration N_i, effective diameter D_e and ice water content IWC. In general, these retrieved properties agree favorably with corresponding aircraft measurements from Krämer et al. (2020, ACP). Plotting median D_e in cloud radiative temperature T_r vs. extinction coefficient α_{ext} space shows that median D_e exhibits a maximum at the warmest cirrus temperatures.
Moreover, $T_r - T_{top}$ (T_{top} = temperature at cloud top), a measure of cirrus geometrical thickness since T_r is typically near the cloud center, also exhibits a maximum at the warmest cirrus radiative temperatures (when related to α_{ext}) at the same α_{ext} value where the D_e maximum occurs. As confirmed by a simple model based on homogeneous freezing nucleation (hom) theory, this α_{ext} value marks a transition from cirrus clouds formed through heterogeneous ice nucleation (het) to cirrus clouds formed through het and hom combined (henceforth hom cirrus). The median N_i value corresponding to this transition is then generalized to all cirrus temperatures, forming a temperature-dependent extinction boundary between these het and hom regions. Lastly, the T_r boundary for hom cirrus corresponds to the T_r below which a D_e maximum is no longer evident.
The analysis that followed allowed us to globally map the fraction of hom cirrus over ocean by season. While in the tropics (± 30° latitude) this fraction is typically $<$ 15%, outside the tropics this fraction varies by $\sim$ 20% to 40%, being highest during the winter ($\sim$ 27% in the NH; $\sim$ 37% in the SH). Estimating the cloud radiative effect (CRE) as the product of cloud frequency of occurrence $\times$ cloud optical depth, the cirrus CRE over ocean outside the tropics appears to be dominated by the hom cirrus fraction.

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1.3 Theory and simulations

1.3.1 Blaž Gasparini (invited)

Universität Wien, Wien, Austria

It's time to clear up uncertainties related to tropical cirrus clouds

Upper tropospheric clouds, especially anvil clouds, are the most abundant and radiatively important cloud type in the tropics. Their properties are controlled by interactions of large-scale and small-scale climate processes. On one hand, their height is constrained by the large-scale climate: on average, convective detrainment occurs at a temperature where water vapor cooling decreases rapidly (about 220 K). On the other hand, their optical thickness and net radiative effects are determined by a variety of small-scale microphysical processes, their interaction with radiation, turbulence, and circulation.

Tiny differences in how ice crystals form, grow, shrink, or interact with solar or terrestrial radiation can lead to large differences in the climatic role of anvils. Such processes are currently not well understood. Their representation in models used for climate projections is very crude and their output should be treated with caution when examining climate projections. Consequently, the tropical anvil cloud feedback is the single largest contributor to the total cloud feedback uncertainty.

Global or limited-domain convectively-resolved models allow us to study the small-scale processes that drive anvil evolution and determine the delicate balance between thick and thin anvil clouds. Because they explicitly resolve deep convection, small-scale processes and particularly microphysics became the dominant source of the inter-model spread and the spread in model responses to global warming. I therefore argue that the move to (global) cloud resolving scales represents an exciting time to work on the uncertain small-scale processes and their coupling to global climate, and conclude by suggesting several strategies to make progress on tropical cirrus in harmony with (global) cloud resolving models and big data.

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1.3.2 Klaus Gierens (invited)

Klaus Gierens and Sina Hofer

Deutsches Zentrum für Luft- und Raumfahrt (DLR), Oberpfaffenhofen, Germany

Cirrus clouds, ice supersaturation, and their dynamical background

Although this conference is on cirrus clouds, we may not forget, that the condition sine-qua-non for cirrus is ice supersaturation. This lecture is therefore on ice supersaturation.
Perhaps not surprisingly, ice supersaturation in the upper troposphere is quite difficult to forecast. As it is an extremal state in the humidity field, it reacts non-linearly to changes in ambient conditions. Water vapour takes place in many different chemical and physical processes and is thus highly variable with strong gradients. Reliable measurements of humidity in the tropopause region are largely lacking, so that there is not much for weather models to assimilate.
In the lecture, we will talk about a related quantity termed upper-tropospheric humidity, a satellite-derived radiation quantity that is intended to describe the humidity field in the UT. We will introduce the contribution and weighting functions and show some applications.
Second we will show how ice supersaturated regions are connected to the dynamic quantities in the synoptic fields and we show how one can try to exploit these dynamic quantities for an improved prediction of ice supersaturation.

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1.3.3 Blaž Gasparini

Blaž Gasparini, Peter N. Blossey, Martina Krämer, Rachel Atlas

Universität Wien, Wien, Austria

Simple microphysical changes improve cirrus representation in cloud resolving models

Despite their large climatic importance, global storm-resolving models are currently not able to reproduce in-situ observations of tropical cirrus. A large source of model disagreement can be traced back to the model's crude representation of ice cloud properties. These processes are important in tropical deep convection and the subsequent formation of anvil cirrus clouds that evolve, spread and thin over their lifetime.
In this study we updated the freezing at cirrus conditions in the Predicted Particle Properties (P3) microphysical scheme of the System for Atmospheric Modeling (SAM) cloud resolving model with an ice nucleation scheme that represents the competition between deposition of vapor on pre-existing ice crystals, homogeneous ice nucleation, and heterogeneous ice nucleation. The modified SAM-P3 model with an idealized representation of the climate of the tropical Pacific reliably reproduces ice cloud properties compared to a compilation of several field campaign datasets from the tropical Pacific. In addition, the implementation of a detrained air tracer gives us an accurate representation of the time since an air parcel left a deep convective plume and a way to separate in-situ formed TTL cirrus from detrained anvil clouds.
While the detailed cold cloud microphysics may be still out of reach for many of the global storm-resolving models, our study also highlights the impact of too restrictive model limiters of microphysical cloud properties, such as the ice crystal number concentration limit. Simply removing such artificial limits substantially improved the agreement between modeled and observed tropical ice cloud properties. As such minor tweaks to the model code come with no extra computational cost, a careful rethinking and relaxing of limiters in the microphysical code may lead to a quick improvement in the global storm-resolving simulations of ice clouds.

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1.3.4 Peter Spichtinger

Peter Spichtinger, Hannah Bergner

Institut für Physik der Atmosphäre, Johannes-Gutenberg Universität, Mainz, Germany

Ice clouds as nonlinear oscillators - a treatment using dynamical systems theory

Ice clouds in the tropopause region, i.e. in the low temperatur regime, are still not well understood. There is still discussion about the dominant formation mechanism and the impact of other processes as e.g. sedimentation. In this study we represent ice clouds in a parcel model as driven by a constant vertical updraft. Thus, we formulate a simple three dimensional system of ordinary differential equations for the variables number and mass concentration of ice crystals and saturation ratio as control variable. We concentrate on homogeneous freezing of solution droplets as a dominant formation process; the processes diffusional growth and sedimentation are also included. We can show that the system is a nonlinear oscillator with two Hopf bifurcations, i.e. there are transitions from a damped to an undamped oscillation depending on the parameters temperature, vertical velocity and (potentially) strength of sedimentation. The resulting values of number concentrations at the equilibrium points and during the oscillations, respectively, compare very well with measurements.

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1.3.5 Hannah Bergner

Institut für Physik der Atmosphäre, Johannes-Gutenberg Universität, Mainz, Germany

Gravity waves and ice clouds – Interaction of dynamics and microphysics using a modelling approach

Ice clouds do have a significant impact on the thermodynamic structure of their environment due to diabatic effects such as latent heat release in phase transitions. On the other hand, the ice clouds themselves are crucially affected by the local dynamics e.g. due to atmospheric gravity waves that could be generated by frontal systems or flow over a mountain.
The interaction of the relevant dynamical processes and ice cloud microphysics, which do have quite different length and time scales, is not yet well understood. We investigate the influence of atmospheric gravity waves on ice cloud microphysics in some exemplary cases using a modelling approach.
The ice cloud properties are modelled by an ODE system where the variables are number and mass concentration as well as the supersaturation of water vapour over ice, while the vertical updraft is externally driving the system. The dynamical effects due to gravity waves are described by a Taylor-Goldstein type equation, which is then used to calculate trajectories of air parcels with represented ice cloud physics. While the ice cloud system can be regarded as a non-linear oscillator for constant vertical motion, more complex behaviour emerges in the case of the non-constant updraft along trajectories.
Due to the non-linearity of the ice cloud model and the overall complexity of the equations of the coupled systems, the feasibility of analytical calculations is limited and the investigation of the coupled system is largely based on numerical approaches

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1.3.6 Stamen Dolaptchiev

S. Dolaptchiev, P. Spichtinger, M. Baumgartner and U. Achatz

Institute for Atmospheric and Environmental Sciences, Goethe University Frankfurt, Frankfurt, Germany

Gravity wave spectra interacting with ice clouds

The effects of non-orographic gravity waves (GW) on ice clouds are, if at all, only crudely parameterized in current climate models. However, observational and modeling studies indicate that GW dynamics crucially affect the ice cloud properties and life cycle. As next generation ray-tracing-based GW parameterizations allow for an improved representation of temporal and spatial GW variability in climate models, a realistic parameterization of the GW-cirrus interactions becomes feasible. Here, we present simplified asymptotic model for homogeneous ice nucleation forced by a superposition of mid- and high-frequency GWs. The asymptotic model is able to reproduce the nucleation events in Lagrangian parcel model and provides simple expression for the nucleated ice crystal number concentration. The statistics of both models are compared and implications of the results for the construction of GW-cirrus parameterizations are discussed.

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1.3.7 Alena Kosareva

Alena Kosareva[1], Stamen Dolaptchiev[1], Peter Spichtinger[2], Ulrich Achatz[1]

[1] Institute for Atmospheric and Environmental Sciences, Goethe University Frankfurt, Germany
[2] Institute for Atmospheric Physics, Johannes Gutenberg University, Mainz, Germany

Homogeneous nucleation of ice particles forced by gravity waves in ICON based on asymptotic solution

Interaction between gravity wave dynamics and microshysical processes has an important role in understanding of formation of in-situ cirrus clouds. However, such multi-scale interactions are poorly represented in climate models, when the small scale processes and interactions have to be parameterised.
One of the approaches to model gravity waves-ice interactions is to use the double-moment scheme, when nucleation, sedimentation and deposition are resolved within the model. In order to be able to represent same physics with less computational effort the asymptotic solution for homogeneous nucleation of ice particles generated by gravity waves was proposed in [S. Dolaptchiev et all. Interactions between gravity waves and cirrus clouds: asymptotic modeling of wave induced ice nucleation. Journal of the Atmospheric Sciences (under revision), 2023]. The method was tested on an idealised parcel model for ice nucleation forced by high- and mid-frequency gravity waves.
Given the good agreement between number concentration of produced ice particles compared to detailed double-moment scheme for parcel model, the asymptotic solution is implemented in the global ICON model. Preliminary assessment of asymptotic solution is made for the real initial condition test case and it shows a good agreement for predicted number concentration of ice particles produced by the double moment scheme explicitly resolving nucleation. Further research presumes coupling of the existing transient multiscale gravity wave model to ice physics scheme allowing for direct gravity wave forcing of ice nucleation.

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1.3.8 Dario Sperber

Dario Sperber, Klaus Gierens

Deutsches Zentrum für Luft- und Raumfahrt (DLR), Oberpfaffenhofen, Germany

Towards a more reliable forecast of ice supersaturation: Concept of a one-moment ice cloud scheme that avoids saturation adjustment

A significant share of aviation's climate impact is due to persistent contrails. Avoiding the creation of contrails that exert a warming impact is thus a crucial step in approaching the goal of climate friendly air transportation. For this purpose, a reliable forecast of when and where persistent contrails are expected to form is needed such that aircraft can be rerouted. One problem on the way to these forecasts is the current systematic underestimation of the frequency and degree of ice-supersaturation on cruise altitudes in numerical weather prediction due to the practice of "saturation adjustment". In this common parameterisation, the air inside cirrus clouds is assumed to be exactly at ice-saturation, while measurement studies have found cirrus clouds to be quite often in an ice-supersaturated state.

In this study, we propose a new ice cloud scheme that overcomes saturation adjustment by explicitly modelling the decay of the in-cloud humidity after nucleation, thereby allowing for both in-cloud super- and subsaturation. To achieve this, we introduce the in-cloud humidity as a new prognostic variable and derive the humidity distribution in newly generated cloud parts from a stochastic box model that divides a model grid box into a large number of air parcels and treats them individually.

The new scheme is then tested against a parameterisation that uses saturation adjustment, where the stochastic box model serves as a benchmark for reality. It is shown that saturation adjustment underestimates humidity both shortly after nucleation, when the actual cloud is still highly supersaturated, and also in aged cirrus if temperature keeps decreasing, as the actual cloud remains in a slightly supersaturated state in this case. The new parameterisation on the other hand closely follows the behaviour of the stochastic box model in any considered case.

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1.3.9 Ulrike Burkhardt

Pooja Verma and Ulrike Burkhardt

Institut für Physik der Atmosphäre, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Oberpfaffenhofen, Germany

Changes in cirrus cloudiness due to contrail formation within cirrus

Contrail formation in ice supersaturated regions increases cloudiness and has been shown to have a large impact on the radiation budget. Contrail formation within natural cirrus has been largely overlooked even though it can introduce a large perturbation in ice crystal numbers modifying microphysical and optical properties. Those changes are observable from space (Tesche et al 2016). We study the contrail formation within cirrus, the resulting cirrus perturbations and their impact on microphysical and optical properties within a high-resolution regional model.

We have implemented a contrail cirrus parameterization within the ICON-LEM and simulate the contrails in 625 meter horizontal resolution over Germany. The model resolves the relevant dynamics leading to cloud formation and is run using initial and boundary data from the German weather forecasting model COSMO. The contrail parameterization calculates the number of ice crystals that nucleate during contrail formation and the fraction of the contrail ice crystals that survive during vortex decent. Ice crystal nucleation, ice crystal loss and vertical distribution during the vortex phase are dependent on atmospheric and aircraft conditions (e.g. temperature, pressure, supersaturation, cloud properties and aircraft weight etc.) and on the properties on the preexisting cirrus.

We study the perturbation in ice crystal number concentration, ice water content and optical depth of those perturbed clouds and the life cycle of the perturbations. Contrail formation has a large impact on the ice crystal number concentration and leads eventually to the perturbation of large parts of the cloud. The associated change in ice crystal sizes leads to a redistribution of water within the cloud. The change in optical depth due to contrail formation is significant. Areas of decreased cirrus ice water content and optical depth can be also found in areas close to contrail induced optical depth increases. This is likely a rapid adjustment resulting from larger water vapor deposition rates in the contrail disturbed areas. Contrail formation within natural cirrus can lead to a faster dissolution of parts of the cirrus in particular in areas that experience drying. Perturbations of cirrus due to contrail formation can persist for many hours.

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1.3.10 Karol Corko

Karol Corko [1], Ulrike Burkhardt [1], Florian Ewal [1], Martin Köhler [2]

[1] Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre, Oberpfaffenhoffen, Germany
[2] Deutscher Wetterdienst, Offenbach, Germany

Evaluation of the tropical upper tropospheric cloudiness simulated by the convection permitting DYAMOND models

Employing a resolution of 5 km or less, DYAMOND models resolve much of the cloud relevant dynamics and better simulate cloud structure and diurnal cycle of precipitation. Nevertheless, cloud properties in DYAMOND simulations vary significantly despite the fact that they resolve deep convection. We focus on evaluating tropical upper tropospheric (UT) ice clouds in high-resolution DYAMOND simulations as the tropics should particularly benefit from the increased resolution because deep convection controls the tropical UT water budget. We analyse the horizontal distribution of total ice water path (TIWP) and its connection to the convective strength, as indicated by the vertical velocity. While the PDF of tropical vertical velocity simulated by the different models is quite similar, the total ice water path (TIWP) connected with those vertical velocities varies strongly. Tropical total IWP is much improved relative to lower resolution models, such as NWP ICON, and generally underestimated compared to active remote sensing. Precipitation, on the other hand, is overestimated. Using precipitation as an indicator for the strength of tropical convection we can compare the associated changes in UT cloudiness to passive and active remote sensing data. We show that in particular for weak convection the UT IWP is underestimated, which is particularly pronounced in lower resolution NWP simulations using parameterized convection. This shows that while cloud scale dynamics is much improved in the high-resolution simulations the microphysics still lead to a large spread in simulated cloud properties. Uncertainty in cloud microphysics prohibits convergence in simulated high cloud properties.

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1.3.11 Simon Unterstrasser

Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre, Oberpfaffenhoffen, Germany

Collection/Aggregation in a Lagrangian cloud microphysical model: Insights from column model applications

Lagrangian cloud models (LCMs), a.k.a. particle-based methods, are considered the future of cloud microphysical modeling in non-operational settings. However, LCMs are computationally expensive due to the typically high number of simulation particles (SIPs) necessary to represent microphysical processes such as collection/aggregation successfully. The representation of collection/aggregation is explored in zero- and one-dimensional column simulations, allowing for the explicit consideration of sedimentation. Two variants of the Lagrangian probabilistic all-or-nothing (AON) collection algorithm are tested that mainly differ in the assumed spatial distribution of the droplet ensemble: The first variant assumes the droplet ensemble to be well-mixed in a predefined three-dimensional grid box (WM3D), while the second variant considers explicitly the vertical coordinate of the SIPs, reducing the well-mixed assumption to a two-dimensional, horizontal plane (WM2D). Both variants are compared to established Eulerian bin model solutions. Generally, all methods approach the same solutions, and agree well if the methods are applied with sufficiently high accuracy (foremost the number of SIPs, timestep, vertical grid spacing). However, it is found that the rate of convergence depends on the applied model variant. Most importantly, the study highlights that results generally require a smaller number of SIPs per grid box for convergence than previous box simulations indicated. The reason is the ability of sedimenting SIPs to interact with an effectively larger ensemble of particles when they are not restricted to a single grid box. Since sedimentation is considered in most commonly applied three-dimensional models, the results indicate smaller computational requirements for successful simulations than previously assumed, encouraging a wider use of LCMs in the future.

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1.3.12 Jhaswantsing Purseed

J. Purseed[1], and N. Bellouin[1,2]

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Large Eddy Simulations of aerosol-cirrus interactions

The indirect effects of aviation-induced aerosols are the least understood and the latest assessment of aviation radiative forcing could not give a best estimate and an uncertainty range [1]. Previous studies [2,3] have shown that a perturbation to the ice crystal number leads to a change in cirrus lifetime and ice water path. In this work, we assumed that aged aviation aerosols have become soluble and we investigate whether their perturbations to ice nucleation can produce large perturbations to cirrus ice crystal number concentration (ICNC). We study these interactions using the 3D Met-Office NERC Cloud model (MONC). MONC is a Large Eddy Simulation model coupled to the cloud micro-physics scheme, CASIM. We simulate two types of cirrus namely the Gravity Wave cirrus (GW) and the Warm Conveyor Belt cirrus (WCB).

For both clouds, we find that perturbing the formation stage of the cirrus cloud by injecting soluble aerosols leads to an increase in ICNC and a decrease in the initial crystal size. Furthermore, the ice clouds created in the presence of the injected soluble aerosols tend to have a higher IWC and an increased lifetime. In contrast, perturbing a pre-existing cirrus with soluble aerosols does not change the properties of the ice cloud. Ice crystal growth by vapour deposition uses available water vapour during the lifetime of the cirrus [5, 6], which we find comes at the expense of activating aerosols that would lead to an increase in the ICNC. Hence, although cirrus clouds would be sensitive to a perturbation in their ICNC, it is difficult to obtain such perturbations by injecting aerosols at cloud level, for example from commercial aircraft exhaust. Furthermore, even though these results do not completely preclude large cirrus perturbations from aviation aerosols in specific cases, they suggest that the corresponding global radiative forcing is small.

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1.3.13 Aurélien Podglajen

A. Podglajen, T. Lesigne, F. Ravetta, R. Plougonven, A. Hertzog

Laboratoire de Météorologie Dynamique, Sorbonne Université (CNRS) Paris, France

Relationship between TTL cirrus and gravity waves: observations from a balloon-borne lidar and idealized numerical simulations

Observational studies over the last decade have suggested a relationship between gravity waves and the occurrence of cirrus clouds in the tropical tropopause layer (TTL). In this poster, the relationship will be explored in a new observational dataset gathered by 3 microlidars which flew for a few months onboard long duration balloons. The balloons were launched in boreal fall 2021-2022 in the frame of the Strateole 2 balloon campaign. Some possible impacts of TTL cirrus on gravity waves will be investigated by the mean of theoretical analysis and idealized numerical simulations.

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1.3.14 Tuule Müürsepp

Tuule Müürsepp, Michael Sprenger, Heini Wernli, and Hanna Joos

Eidgenössische Technische Hochschule (ETH) Zürich, Zürich, Switzerland

Radiative heating profiles in different parts of cirrus clouds associated with extratropical cyclones

Extratropical cyclones are typically associated with an elongated band of mixed-phase clouds, capped with a cirrus shield that is up to 3-km deep. These large-scale cloud features, consisting of air with different origin, are associated with complex interactions with the long- and shortwave radiation. More specifically, these clouds can be produced by ascending airstreams in extratropical cyclones, the so-called warm conveyor belts (WCBs). As WCBs are considered the most cloud-producing phenomena in extratropical cyclones, it is important to understand and characterize the interaction between the clouds, radiation, and the dynamics of these airstreams. In this study, we use ERA5 reanalyses and air parcel trajectories to take a closer look at the cirrus cloud that forms at the end of the ascent of WCBs (WCB outflow). We investigate the cloud structure by determining the origin of the cloud forming air parcels and their hydrometeor history based on the trajectory calculations. The analysis shows that the WCB ice cloud exhibits a complex pattern of origins, radiative temperature tendencies and the associated modification of potential vorticity, which serves directly to analyze the impact of the cloud-related radiative heating rates on the atmospheric circulation and in particular cross-tropopause transport of humidity and atmospheric constituents. This project about extratropical cloud-radiation-circulation interactions furthers the process understanding with the help of an offline version of ECRAD, the latest radiation scheme for the ECMWF Integrated Forecast System, which we use for sensitivity analyses of how different cloud structures in WCB outflows influence the vertical profile of radiative heating.

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1.3.15 Anthony Baran

Anthony J. Baran[1,2], James Manners[1], Paul Field[1,3], Kalli Furtado[4], and Adrian Hill[5]

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[3] University of Leeds, U. K.
[4] National Environment Agency, Singapore.
[5] European Centre for Medium Range Weather Forecasts, U. K.

A first consistent coupling between aerosol–ice interactions and radiation, and its impact in a high-resolution weather model

The latest assessment of the Intergovernmental Panel on Climate Change (IPCC) report that there is significant uncertainty in the radiative effect of aerosol–ice interactions on the Earth's atmosphere radiation balance. This is partly owing to the lack of knowledge of the interaction between aerosol and ice, and how this interaction evolves the ice particle shapes, and particle size distribution (PSD). This is further exacerbated by the fact that current cloud–aerosol interaction models cannot adequately address this radiative uncertainty owing to an inherent lack of consistency between the two-moment microphysics and the evolving radiation fields. In this poster, we address this lack of consistency by directly coupling the Cloud–AeroSol Interacting Microphysics (CASIM) model generated prognostic moments (i.e. mass and number) to the ice optical properties through the same assumed PSD, the generalised gamma function. The bulk ice optical properties are calculated from the ensemble model of cirrus ice crystals at 175 wavelengths between 0.175 and 100 µm. The parametrization of CASIM's two-moments with the bulk ice optics is very accurately achieved using Padé approximants expressed as functions of the mass-equivalent spherical diameter. We examine the impact of this consistent coupling on the outgoing top-of-atmosphere (TOA) short– and long–wave irradiance fields in the Met Office's high-resolution regional model, which was centered around Darwin, Australia, and compare them to the CERES short– and long–wave local midday irradiance measurements. We show that the consistent moment–ice optical coupling considerably better describes the probability density function (PDF) of the CERES short–wave and long–wave irradiance measurements than the current operational model ice optical parametrization.

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1.3.16 Edgardo Sepulveda Araya

Edgardo I. Sepulveda Araya[1], Sylvia Sullivan[1], Emma Järvinen[2], Guanglang Xu[2], and Aiko Voigt[3]

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[2] Institute for Meteorology and Climate Research, Karlsruhe Institute of Technology, Karlsruhe, Germany
[3] Department of Meteorology and Geophysics, University of Vienna, Vienna, Austria

A Two-Fold Approach to Quantify Ice Cloud-Radiative Heating Rate Sensitivity to Cloud Optical, Macro and Microproperties

Ice clouds play a key role in the atmospheric radiation budget, both by reflection of shortwave radiation and absorption-emission of longwave radiation. Through these radiative interactions, ice clouds can set atmospheric temperature gradients and thereby influence atmospheric circulation regimes. The radiative signature of ice clouds strongly depends on their macro- and microphysical characteristics, as well as their optical properties. While the new generation of storm-resolving models improves the representation of the vertical velocities that drive cloud formation, subgrid scale differences, for example in ice optics and microphysics, generate large variability in the modeled atmospheric cloudradiative heating (CRH) rates (Sullivan and Voigt, 2021).

We propose both an idealized single-column and more realistic two-dimensional transect approach for investigating CRH, using the new ecRad radiative transfer module (Hogan and Bozzo, 2018). First, in a series of single-column calculations, we evaluate the impact of realistic perturbations in macro- and microphysical properties, such as cloud-top temperature and ice crystal effective radius, on CRH. For this approach, a heating sensitivity matrix visualization is presented as the response for the different levels of macro-micro properties perturbations. Secondly, we study the impact of using three different ice optical schemes (Fu, 1996; Fu et al., 1998; Yi et al., 2013; Baran et al., 2016) on CRH over three latitudinal transects located in the Eastern Pacific, Western Pacific, and passing over the Asian Monsoon Area. For each of these transects, ecRad is driven by realistic atmospheric conditions provided by ERA5.

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1.3.17 Samantha Turbeville

Samantha Turbeville (presenter), Jacqueline Nugent, Thomas Ackerman, Peter Blossey, and Chris Bretherton

Department of Atmospheric Sciences, University of Washington, Seattle, WA, USA

How much does microphysics matter for simulating cirrus clouds?

Cirrus cloud processes range across spatial scales from micrometers to kilometers, forming in minutes but persisting for days. Cloud-resolving models (CRMs), which do not parameterize deep convection or cirrus clouds, may more accurately represent convective processes but still require a variety of subgrid parameterization schemes, which may contribute to the differences in predicted ice cloud properties. In previous work using global CRMs from the DYnamics of the Atmosphere Modeled on Nonhydrostatic Domains (DYAMOND) project, we find that simulated cirrus vary greatly between models. This uncertainty in simulating cirrus can have significant impacts on the top-of-atmosphere radiative energy balance. In the current study, we investigate how much microphysical parameterizations matter for simulating cirrus clouds in high-resolution models by performing a microphysical parameter sensitivity study within one CRM. Previous studies have shown that cirrus clouds are highly impacted by the choice of microphysics scheme in models, but here we quantify how changes within the P3 microphysics scheme in the Simple Cloud-Resolving E3SM Atmosphere Model (SCREAM) can impact the optical and radiative properties of simulated cirrus clouds. A small-domain doubly-periodic version of SCREAM is used as a testbed for the global CRM. We look at how microphysical changes to ice processes impact cirrus lifetime, convective texture, and the surrounding environment, especially focusing on the tropical tropopause layer. We find that microphysical parameterization choices greatly affect simulated cirrus cloud properties while the overall texture of convection remains consistent. As time permits, we also consider how sensitive future predictions are of the earth system to microphysical parameterization choices by increasing sea surface temperatures.

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2 Mixed phase clouds

2.1 In-situ measurements

2.1.1 Greg McFarquhar (invited)

Cooperative Institute for Severe and High Impact Weather Research and Operations and School of Meteorology, University of Oklahoma, Norman, OK

In-Situ Measurements of Mixed-Phase Clouds: What is State of Art and What are Ongoing Challenges

Mixed-phase clouds, that consist of mixtures of ice and liquid, are prevalent across the globe from the Tropics to the poles. Based on the Wegener-Findeisen-Bergeron process, one would expect ice crystals to grow at the expense of water droplets, yet these clouds are pervasive due to a delicate balance between cloud top radiative cooling, microphysical heating, ice sedimentation and large-scale forcing. Because processes occurring in mixed-phase clouds impact the life cycle of clouds, and water and energy budgets on global and regional scales, it is critical that their properties be well understood. Although in-situ observations do not have the temporal and spatial coverage of remote sensing retrievals, they allow a fine-scale view on the structure of these clouds that cannot be obtained any other way and is critical for evaluating theoretical, modeling and remote sensing studies.

Mixed-phase clouds offer unique challenges for measuring cloud properties in-situ: 1) mixed-phase clouds are very horizontally inhomogeneous so properties need to be measured on as fine of a spatial scale as possible, yet the small sample volumes of in-situ probes, especially those measuring large particles, complicate the ability to do this; 2) the limited resolution of imaging probes can make it difficult to resolve differences between ice crystals and supercooled droplets at small sizes, complicating phase identification algorithms; 3) corrections for the size and shape of out of focus particles are uncertain for non-spherical particles, making it difficult to quantify properties and even the phase of these particles; 4) the small and highly uncertain depth of field for small particles on imaging probes, as well as the shattering of large crystals on probe tips, complicates the analysis of cloud properties; and 5) it is difficult to measure the humidity in mixed-phase clouds with the needed time response and accuracy to understand turbulent growth mechanisms. This presentation summarizes state of art methods for measuring and analyzing the single particle properties, bulk properties, and fine-scale structure of mixed-phase clouds using in-situ measurements. Key knowledge gaps inhibiting our understanding of mixed-phase cloud processes are also identified from both an instrument-measurement perspective and from the perspective of where more in-situ measurements of mixed-phase clouds are needed. Synergies with theoretical, modeling, and remote sensing studies are also discussed.

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2.1.2 Andy Heymsfield (cancelled)

Andrew Heymsfield (NCAR), Aaron Bansemer (NCAR), Gerald Heymsfield (NASA), Darin Toohey (CU)

National Center for Atmospheric Research (NCAR), Boulder, Colorado

Microphysics and Dynamics of Snow Band and Generating Cells from IMPACTS: Snow Production Rates

This study uses in-situ and coincident overflying aircraft data from the NASA IMPACTS field program to study the role of snow band and generating cell dynamics on the production of snow from East Coast United States snowstorms. Data from field programs in 2020, 2022 and 2023 are used in this analysis. In-situ data, including microphysical probe measurements over a wide range of particle sizes, and 3D wind measurements and water vapor measurements, are collected from the NASA P3 aircraft. Snowfall rates are calculated from the particle probe size spectra measurements, drawing on the particle images and direct measurements of the condensed water content to estimate particle mass. Remote sensing data-Doppler radar measurements for X, Ku, Ka and W bands are used to refine the estimates of snowfall rates and their vertical distribution through the cloud depth.

Vertical motions are found to be in the range $-2 < w < 4$ m/s. Snowfall rates are enhanced in the updraft regions, with increasing rates with vertical velocity. The liquid water content scales with the vertical velocity. The particle size distributions within the snowbands are broader than those outside of the snowbands. The Doppler radar measurements-reflectivity, provides a means of determining the increase in snowfall rates as a function of temperature and vertical velocity. Data from many snow bands sampled over the three years are synthesized to provide an illustration of the growth of snow in snowbands.

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2.1.3 Jan Henneberger

Jan Henneberger[1], Fabiola Ramelli[1], Robert Spirig[1], Christopher Fuchs[1], Maxime Hervo[3], Anna Miller[1], Kevin Ohneiser[2], Nadja Omanovic[1], Martin Radenz[2], Michael Rösch[1], Patric Seifert[2], Huiying Zhang[1], Ulrike Lohmann[1]

[1] Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland
[2] Leibniz Institute for Tropospheric Research (TROPOS), Leipzig, Germany
[3] Federal Office of Meteorology and Climatology MeteoSwiss, Payerne, Switzerland

Bridging the ice crystal growth knowledge gap by seeding supercooled stratus clouds with a UAV

Ice formation and growth in clouds are crucial for precipitation initiation, but the current understanding of these processes remains limited, leading to uncertainties in weather forecasts and climate projections. The CLOUDLAB project aims to bridge this gap by using supercooled stratus clouds as a natural laboratory for glaciogenic cloud seeding experiments: Ice nucleating particles are dispersed into wintertime stratus clouds via an Uncrewed Aerial Vehicles (UAV), triggering ice crystal formation and subsequent growth. The combination of UAV and persistent stratus clouds enables repeated seeding experiments under well-constrained initial conditions.

A total of 52 seeding experiments were conducted at seeding temperatures between -10°C and -3°C in clouds over the Swiss Plateau. State-of-the-art remote sensing instruments (e.g., scanning cloud radar) and in-situ equipment (e.g., aerosol spectrometer and holographic imager mounted on a tethered balloon) monitored seeding-induced microphysical changes. Results showed significant increases in ice crystal and aerosol number concentrations inside the seeding plume, with ice crystals growing to diameters of 100-400 µm within 3-15 minutes of formation, while the Wegener-Bergeron-Findeisen caused a simultaneous decrease in the cloud droplet concentration. Because multiple seeding experiments can be conducted under similar environmental conditions and because the location of the release of ice nucleating particle is known, the experimental approach of CLOUDLAB allows laboratory-like experiments in a natural environment by changing one experimental parameter (e.g., seeding distance). The findings are contextualized with a numerical weather model (ICON) to improve the representation of ice formation and growth processes in the microphysics scheme.

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2.1.4 Simon Kirschler

Deutsches Zentrum für Luft- und Raumfahrt (DLR) Oberpfaffenhofen, Oberpfaffenhofen, Germany

Initiation of the ice phase promotes precipitation in the western North-Atlantic Ocean

One of the regions with large intermodel spread of the Coupled Model Intercomparison Project Phase 6 ensemble is the western North-Atlantic Ocean. In this region, predominantly shallow and broken cloud systems with mixed-phase clouds form during winter. We performed comprehensive measurements of boundary layer clouds during the NASA Aerosol Cloud meTeorology Interactions oVer the western ATlantic Experiment (ACTIVATE) mission. Here we present a statistical evaluation of individual cloud events probed by the Fast Cloud Droplet Probe and the Two-Dimensional Stereo cloud probe during 155 research flights in a representative and repetitive flight strategy allowing for robust statistical data analyses. We show that the utilization of multiple phase spaces of microphysical parameters provides access to a classification of cloud and precipitation, which were partitioned into liquid and mixed-phase. We then compare microphysical properties of pure liquid clouds to mixed-phase clouds and show that the initiation of the ice phase in mixed-phase boundary layer clouds promotes precipitation over the western North-Atlantic Ocean during winter. The spatial distribution shows that in winter most of the cloud measurements are associated with precipitation in the same area, while precipitation is measured less frequently during summer. The ACTIVATE dataset is particularly well suited to investigate the processes that give rise to liquid and mixed-phase clouds, ice and precipitation.

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2.1.5 Nina Maherndl

N. Maherndl[1], M. Maahn[1], M. Moser[2,3], J. Lucke[3], M. Mech[4], N. Risse[4]

[1] Leipzig Institute of Meteorology (LIM), University of Leipzig, Germany
[2] Institute for Physics of the Atmosphere, Johannes Gutenberg-Universität, Mainz, Germany
[3] Institute for Physics of the Atmosphere, German Aerospace Center (DLR), Wessling, Germany
[4] Institute for Geophysics and Meteorology, University of Cologne, Cologne, Germany

Airborne observations of riming in arctic mixed-phase clouds during HALO-(AC)^3

Ice crystal formation and growth processes in mixed-phase clouds (MPCs) are not sufficiently understood leading to uncertainties of atmospheric models in representing MPCs. One of these processes is riming, which occurs when liquid water droplets freeze onto ice crystals. Riming plays a key role in precipitation formation in MPCs by efficiently converting liquid cloud water into ice. However, riming is challenging to observe directly and there are only few studies quantifying riming in Arctic MPCs.
In this study, we derive the normalized rime mass M to quantify riming. We use airborne data collected during the (AC)^3 field campaign HALO-(AC)^3 performed in 2022. For this campaign, two aircraft were flying in formation collecting closely spatially collocated and almost simultaneous in situ and remote sensing observations.
We aim to quantify M by two methods. First, we present an Optimal Estimation algorithm to retrieve M from a combination of radar reflectivity Z_e and in situ particle size distribution (PSD) measurements. We use the Passive and Active Microwave radiative TRAnsfer tool (PAMTRA) to simulate Z_e from the PSD and find M by matching to the measured Z_e. In the forward simulation, we use empirical relationships of M and particle properties, which are derived via aggregation and riming model calculations. Second, we derive M from in situ measured particle shape. We calculate the complexity χ of in situ measured particles, which relates particle perimeter to area. We then derive M from empirical relationships that were again obtained from synthetic particles. We compare the obtained M derived by both methods and evaluate the occurrence of riming in terms of meteorological conditions and macrophysical cloud properties to understand external drivers and variability of riming.
This will lead to a better understanding of riming and thereby helps to improve modelling of this important arctic MPC process.

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2.1.6 Jeffrey R. French

University of Wyoming, Laramie, WY, US

Airborne Observations of Super-cooled Drizzle, Secondary Ice Production, and Mixed Phase Clouds during WINTRE-MIX

The Winter Precipitation Type Research Multi-scale Experiment (WINTRE-MIX) was designed to investigate the role of multi-scale processes influencing variability and predictability of precipitation-type (rain, freezing rain, freezing drizzle, snow, and ice pellets) in near-freezing surface conditions. The six-week campaign was conducted 1 February – 15 March 2022 in SE Canada/NE United States. The campaign utilized an extensive ground-based network of meteorological sensors, mobile sounding systems, three mobile radars, and the National Research Council (NRC) of Canada Convair-580 research aircraft. The NRC Convair provided in situ measurements of thermodynamics, dynamics, and cloud microphysical properties such as hydrometeor phase, shape, and size-resolved concentration.

In this study we present a range of observations from several cases in WINTRE-MIX. We explore the range of sub-0 C cloud conditions sampled by the Convair and the subsequent diverse cloud microphysical characteristics encountered. A few cases are highlighted that include production of supercooled drizzle up to several hundred microns in diameter at temperatures as low as -14C, glaciation of an otherwise liquid-dominated cloud through secondary ice production (presumably rime-splintering), and the re-freezing of previously melted rain drops in near-surface cold layers.

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2.1.7 Christopher Hohman

University of Wyoming, Laramie, WY, US

Simulation of Glaciogenic Cloud Seeding Case During SNOWIE

The Weather Research and Forecasting Weather Modification (WRF-WxMod) model has demonstrated to reasonably simulate the physical processes of glaciogenic seeding in orographic clouds over the mountains of SW Idaho, USA (Xue et al 2022). Xue et al simulated a case from the Seeded and Natural Orographic Wintertime clouds – the Idaho Experiment (SNOWIE) that contained little natural precipitation and showed distinct seeding signals in the observational data. Results from that simulation were validated against observations from a suite of instruments deployed during the SNOWIE campaign that included precipitation gauges, ground-based and airborne radars, and in situ airborne cloud and precipitation probes.

In this study we utilize WRF-WxMod to simulate another case from SNOWIE that also contained unambiguous seeding signals in the observations that has yet to be reported in the literature. The event occurred on January 8, 2017. Relatively shallow orographic clouds produced freezing drizzle with widespread light snow and isolated pockets of moderate snow at the surface. Observations from the University of Wyoming King Air (UWKA) research aircraft recorded cloud top temperatures between -11°C and -16 °C at flight levels. Observed maximum cloud droplet concentrations were 35 cm^{-3}. Drizzle, in isolated pockets, was also observed with drizzle mass content up to 1 g m^{-3}, and natural ice crystal concentrations did not exceed 0.3 L^{-1}. This poster focuses both on the natural evolution of these clouds using WRF together with in situ observations and ground-based radar data, and the evolution and impact of glaciogenic seeding in this case using principally WRF-WxMod constrained by the observations.

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2.1.8 Samatha Clarke

Samantha J. Clarke[1], Paul Field[1,2], Benjamin J. Murray[1], Erin Raif[1], Mark D. Tarn[1], Polly B. Foster[1], Joseph Robinson[1], James B. McQuaid[1].

1: Institute for Climate and Atmospheric Science, University of Leeds, Leeds, UK.
2: Met Office, Exeter, UK.

The M-Phase project – Overview and Regional Modelling Plans

The cloud-phase feedback is a source of major uncertainty in climate projections. The response of shallow mid- and high-latitude mixed-phase clouds to changes in climate is one of the largest components of this uncertainty. This uncertainty is largely due to our lack of present-day knowledge of the microphysical processes occurring in these types of clouds, particularly, in how much ice they contain and to the notoriously poor representation of ice-related processes in models, with most models even neglecting any representation of the particles that trigger ice formation – ice-nucleating particles (INPs). The M-Phase project aims to address these causes of uncertainty by obtaining extensive observations of the present-day conditions in these shallow mixed-phase environments through two flight campaigns (Labrador Sea and Barents Sea). Each of these flight campaigns observed a type of mixed-phase shallow clouds called cold air outbreaks (CAOs) across two environments with differing sea surface temperature (SST) and ice nucleating particle (INP) concentrations and sources. Regional modelling using the UK Met Office Unified Model (MetUM) is conducted for each of the flight campaign cases at high resolution (1 and 2 km) allowing for explicit representation of convection. Each case is simulated for a 36 hour forecast across an approximately 1000 km domains. Regional modelling output is then compared to observations to determine how well represented the CAOs are in the models.
In the future, we will modify various variables and parameters in the regional models such as those related to microphysical processes (e.g. primary and secondary ice production and the assumed sub-grid overlap between ice and water). These modifications should improve the representation of these clouds in regional models and enhance our understanding of the microphysical processes occurring in shallow mixed-phase clouds, particularly in how they respond to differing SST and INP environments therefore reducing the uncertainty in how mixed-phase clouds will respond to changes in climate.

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2.2 Remote sensing observations

2.2.1 Leonie von Terzi

Leonie von Terzi, Christoph Siewert, Axel Seifert, Jan-Niklas Welss, Stefan Kneifel

Universität München, München, Germany

Ice microphysical processes in the dendritic growth layer: can we close current knowledge gaps by combining novel cloud radar observations with Lagrangian Monte-Carlo particle modeling?

The dendritic growth layer (DGL), centered around -15°C plays a key role in the formation of precipitable ice and snow particles. Particle growth by vapour deposition and subsequent aggregation are strongly enhanced in the DGL. As a result, multiple radar observables display distinct features in the DGL related to the plate-like particle shapes as well as rapid formation of aggregates. Recent studies have further found an increase in ice particle number concentration (IPNC) within the DGL. It is unclear where these new particles originate from and if this increase in ice particle concentration influences or even triggers the strong aggregation in the DGL.
In this contribution, we combine zenith triple-frequency (X, Ka, W-band) spectral and slant-viewing W-band spectral polarimetric radar observations with Monte-Carlo Lagrangian particle modeling, linked by a polarimetric forward operator. While polarimetric radar observations are sensitive to small, asymmetric ice particles, the multi-frequency approach can provide information about aggregation and riming. The Lagrangian super-particle model McSnow allows us to describe the microphysical process on the detailed particle level and with that track their individual history. Recently, a habit prediction scheme, predicting the evolution of ice crystal shape and density and an ice-ice collision fragmentation scheme have been implemented. Ice habit, particle size, density and fall velocity are core information for radar forward simulations, facilitating the comparison with polarimetric observations and allowing to link the radar observations to specific ice microphysical processes. The simulations suggest that the increase in ice particle number concentration might be linked to fragmentation. However, contrary to expectation, the increase in number concentration does not seem to influence or trigger the strong aggregation observed in the DGL.

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2.2.2 Anna Weber

Anna Weber, Veronika Pörtge, Lea Volkmer, Tobias Zinner, Bernhard Mayer

Universität München, München, Germany

Remote sensing of cloud thermodynamic phase from spectral and multi-angle polarimetric imaging

We present a method to retrieve cloud thermodynamic phase from multi-angle polarimetric and spectral imaging. Spectral absorption differences between water and ice in the near infrared are commonly used to discriminate between liquid, mixed, and ice clouds. For example, the spectral slope between 1500 and 1700 nm increases with increasing liquid cloud fraction. These methods are very sensitive to small amounts of ice in liquid clouds. On the other hand, the polarization signal of clouds shows different features depending on the cloud thermodynamic phase. The cloudbow is formed by single scattering on liquid cloud droplets. Observation of the cloudbow indicates the presence of liquid water while its absence indicates pure ice clouds. In addition the slope of the Q component of the Stokes vector for scattering angles in the range of 60° to 100° depends on the partitioning between liquid and ice phase. The polarimetric method is much more sensitive to small amounts of liquid water compared to the spectral method and represents cloud thermodynamic phase at cloud top. In addition, polarization is dominated by single scattering and thus does not suffer from 3-D radiative effects.
Both methods are applied to data of the airborne hyperspectral and polarized imaging system specMACS measured during the HALO-(AC)3 campaign. specMACS provides wide-field and high spatial resolution data with horizontal resolution down to a few 10m. By a combination of the spectral and multi-angle polarimetric observations we will retrieve cloud thermodynamic phase partitioning of single layer mixed-phase clouds and investigate spatial and temporal time scale of phase transitions in low-level arctic mixed phase clouds.

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2.2.3 Johanna Mayer

Johanna Mayer, Luca Bugliaro, Florian Ewald, Christiane Voigt

Deutsches Zentrum für Luft- und Raumfahrt (DLR) Oberpfaffenhofen, Oberpfaffenhofen, Germany

A probabilistic approach to determine the thermodynamic cloud phase using passive satellites

The cloud thermodynamic phase (ice / mixed-phase / liquid) is a crucial parameter to understand the earth radiation budget, hydrological cycle and atmospheric thermodynamic processes. The phase partitioning of clouds and their parameterization in global climate models have therefore become of particular interest.

To improve our understanding of the frequency of occurrence and temporal evolution of cloud phase, geostationary passive sensors can be very useful due to their wide field of regard and high temporal resolution. However, the retrieval of cloud phase using passive instruments is challenging since the spectral signature of the phase is weak compared to other parameters of the clouds and atmosphere. Especially the distinction between ice and mixed-phase clouds is difficult and previous efforts to retrieve cloud phase often only distinguished between ice and liquid phase.

We present a new method to detect clouds and retrieve their phase using the passive instrument SEVIRI aboard the geostationary satellite Meteosat Second Generation. The method uses probabilities derived from active observations (the Lidar-Radar product DARDAR) of cloud top phase. Combining these probabilities for different SEVIRI channels gives probabilities for the presence of a cloud and for its cloud top phase. Our probabilistic approach includes a measure of uncertainty and allows us to distinguish between ice, mixed-phase, supercooled liquid, and warm liquid clouds. The method is tested against active satellite measurements and shows good agreement. Finally, we discuss its advantages and limitations. In the future, we plan to use our method to study the microphysical (such as optical thickness and effective radii) and macrophysical (such as temporal evolution and extent) properties of ice and mixed-phase clouds.

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2.2.4 Barbara Dietel

Barbara Dietel, Odran Sourdeval, Sarah Paratoni, Corinna Hoose

Karlsruher Institut für Technologie (KIT), Karlsruhe, Germany

The phase of midlevel and lowlevel clouds over the Southern Ocean and the Arctic Ocean

This study investigates the phase of midlevel and lowlevel clouds over the Southern and the Arctic Ocean from 2007 and 2008. The DARDAR dataset provides a detailed phase categorization based on CloudSat and CALIPSO measurements. Besides the cloud phase partitioning, correlations of the cloud top temperature, vertical cloud thickness, and the horizontal cloud extent with the cloud phase are analysed. A local minimum in the mean liquid fraction within a cloud column can be observed for a cloud top temperature of -15 °C. This hints at processes producing ice at these temperatures, which could be habit dependent vapour growth, secondary ice production, or a combination of both processes, as already discussed in other studies. Furthermore, a hypothesised influence of sea ice coverage on the cloud phase is analysed based on observations of a passive microwave satellite instrument. It can be seen that lowlevel clouds with equal cloud top temperature show a higher liquid fraction if they occur over sea ice compared to clouds over the open ocean. Midlevel clouds over the Southern Ocean show the same behaviour, while the phase of midlevel clouds over the Arctic Ocean shows no dependence on the sea ice conditions. As the release of sea spray aerosols is discussed as a reason for the phase dependence on sea ice coverage, CAMS aerosol reanalyses are used to investigate the cloud phase dependence on different concentrations of various aerosol types within the clouds. An increased sea salt aerosol concentration correlates with an increased ice fraction in lowlevel clouds. This effect is especially pronounced over the Southern Ocean. A brief comparison of the satellite observations with the representation of the phase of midlevel and lowlevel clouds in ICON simulations of the DYAMOND project has shown a lack of supercooled liquid water in lowlevel and midlevel clouds over the Southern Ocean.

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2.3 Theory and simulations

2.3.1 Anna Jaruga (invited)

California Institute of Technology (Caltech), Pasadena, USA

The fundamentals of microphyics in mixed phase clouds

Mixed-phase cloud microphysics is one of the least understood aspects of cloud physics. The system thermodynamics deals with three phases of water and is often out of equilibrium. The particles that make up mixed-phase clouds come in different sizes, shapes, and densities, and the theoretical understanding of some of the processes that affect them is limited.

This talk is intended as an overview of the microphysical processes in mixed-phase clouds including primary ice nucleation, secondary ice production, the WBF process, collisions, breakup and riming. I will focus on the theory of the different microphysics processes, and also discuss their representation in numerical models.

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2.3.2 Anna Possner (invited)

Goethe-Universität Frankfurt, Frankfurt, Germany

Importance of mixed-phase cloud processes for cloud dynamics and cloud radiative effects in the climate system

It is well known, that mixed-phase cloud processes dominate precipitation formation in the climate system. Meanwhile, interactions between mixed-phase cloud processes, cloud dynamics, and the cloud radiative effect in a changing climate remain more elusive. In this talk I will discuss current hypotheses from the scientific literature and their potential implications for the current and future climate.

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2.3.3 Tim Lüttmer

Johannes Gutenberg-Universität Mainz, Mainz, Germany

Cirrus in WCB outflow: in-situ vs liquid origin

Warm conveyor belts (WCB) lead to formation of horizontally wide spread Cirrus clouds in the upper troposphere. However, the contribution of different ice formation processes and the resulting micro- and macrophysical properties of the Cirrus ,e.g., their radiative effects are still poorly understood. We want to especially address the research question of in-situ vs. liquid origin ice formation.
Common microphysics bulk schemes only consider a single ice class which includes sources from multiple formation mechanisms. We developed and implemented a two-moment microphysics scheme in the atmosphere model ICON that distinguishes between different ice modes of origin including homogeneous nucleation, deposition freezing, immersion freezing, homogeneous freezing of water droplets and secondary ice production from rime splintering, frozen droplet shattering and collisional break-up, respectively. Each ice mode is described by its own size distribution, prognostic moments and unique formation mechanism while still interacting with all other ice modes and microphysical classes like cloud droplets, rain and rimed cloud particles.
Using this novel microphysics scheme we can determine the contribution of the various ice formation mechanisms to the total ice content. For the first time this allows us to directly investigate the competition of in-situ and liquid origin Cirrus as well as homogeneous and heterogeneous ice nucleation with regards to environmental conditions and choice of microphysical parameterisations.
We performed an ensemble of simulations for selected WCB cases to cover a range of microphysical properties and compared the results of our liquid origin vs in-situ analysis with other Cirrus categorization algorithms.

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2.3.4 Theresa Kiszler

University of Cologne Institute of Geophysics and Meteorology, Cologne, Germany

Studying the representation of macro- and microphysical cloud properties at Ny-Ålesund in ICON

Clouds play a role in the changing Arctic climate, and are currently the cause for large uncertainties in climate projections. Therefore, we used the ICON model and a large set of observations to study the representation of clouds in the model for an Arctic location (Ny-Ålesund, Svalbard). ICON was used in the LEM version with a Smagorinsky turbulence parameterization, two-moment microphysics and lateral boundary conditions on a limited area with 600m resolution. Using several months of these simulations, we evaluated the representation of the liquid water path, integrated water vapour, as well as vertical profiles of humidity and temperature. We found a good agreement in the large-scale dynamics and variables between the model and observations we used from the super-site AWIPEV which is located in Ny-Ålesund. As next step we are working on understanding the deficiencies which we found related to the phase-partitioning in the clouds. The phase-partitioning showed too much ice production in the model. To achieve this goal we created a tool to output the process tendencies of the 2-moment microphysics scheme, implemented in ICON. With this we are evaluating the role each microphysical process plays for the development and evolution of the clouds. The previously run simulations are used to identify the influence of specific processes under certain environmental conditions on the increased ice production. We focus on low-level clouds as these are often observed to be mixed-phase and provide good observational data coverage. We will show first results of our analysis, which show that only very few processes actually determine the phase-partitioning in the cases we studied.

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2.3.5 Alberto De Lozar

Alberto De Lozar[1], Axel Seifert[1], Ulrich Blahak[1]

[1] Deutscher Wetterdienst, Research and Development Physical Processes, Offenbach am Main, Germany

Adjusting microphysical processes in observational space

In order to improve our weather forecast we have reexamined many of the assumptions in our two-moment microphysical scheme. We mostly concentrate on ice processes, as they typically depend on uncertain parameters and/or parameterizations. We follow a top-down approach in which simulations and observations are compared in observational space using complex forward operators. After looking at case studies, we evaluate how the model performs by comparing statistical quantities averaged over a month. In this presentation we summarize how we have modified the microphysics over the last years to attain more realistic clouds and convection. We have found that high clouds compare better to satellite observations when increasing the rate of collisions of ice particles; that reflectivity in stratiform regions associated to deep convection become more realistic when using a slow graupel velocity and non-spherical capacitances for condensation/evaporation of ice and snow; and that the prediction of rain benefits from using the classical exponential size distribution for rain droplets.

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2.3.6 Christoph Siewert

Christoph Siewert, Jan-Niklas Welß, Simone Wald, and Axel Seifert

Deutscher Wetterdienst, Offenbach am Main, Germany

The particle-based mixed-phase microphysics model McSnow

We will discuss the recent developments on the particle-based mixed-phase microphysics model McSnow. Due to the particle-based approach we can avoid the traditional cloud microphysics model assumptions, i.e. the form of the size distribution can evolve freely and the particle properties can change continuously without the need of categorization.

Besides the ice microphysical processes of sedimentation, vapour deposition, aggregation, and riming, the model can also handle melting and freezing, i.e. mixed-phase particles and pure liquid particle, i.e. rain including the collisional break-up process. A habit-prediction for ice monomers was recently added. Currently we work on utilizing this prognostic ice geometries to sample the geometric variability during aggregation, i.e. the different forms of snowflakes.

This detailed model is run with a fixed 1D atmosphere background for validation and process studies, e.g. comparisons with multi-frequency polarmetric radar observations are ongoing. It can also be coupled to the numerical weather prediction model ICON to perform 2D or 3D simulations. However, those simulations are limited to case studies due to the enormous computational costs. One way to bridge the gap to coarse-grained and computationally efficient algorithms is to use machine learning methods. Similar to classical parametrization we learn the individual physical process rates of the ODE system of bulk variables from these highly-resolved reference simulations.

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2.3.7 Gabriella Wallentin

Karlsruher Institut für Technologie (KIT), Karlsruhe, Germany

Arctic Mixed-phase Multilayer Clouds: A simulation study in search of cloud ice

Multilayer clouds are a frequent phenomenon in the Arctic and to study these in detail the ICON model is set-up in a limited area mode at 1.6km grid spacing with refined nests down to 100m LES. Initial runs show an overestimation of liquid water and a substantial lack of ice in the boundary layers. The liquid water can be scaled down to observational values using the aerosol and reactive trace gases module (ART) with prognostic sea salt to determine the CCN concentration, while the lack of ice has proved more complicated and our efforts in simulating more cloud ice will be shownon this poster.

Here we present comprehensive sensitivity experiments for a two-day case study in early September 2020, observed during the MOSAiC campaign in the high Arctic. Focus is on the microphysical interplay between an upper layer ice cloud and a bottom layer mixed-phase cloud, where seeding from the top layer can lead to total glaciation of the lower layer. The various simulations we will show include (i) the sensitivity tests on CCN concentration as well as the application of ART, (ii) INP sensitivity studies using the default parameterisation, (iii) changes to the default parameterisation to account for high temperature activated INP, (iv) preliminary secondary ice experiments.

Early results still show a lack of ice, which poses the question, what are we missing in the model?

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2.3.8 Roland Schrödner

Leibniz Institute for Tropospheric Research (TROPOS), Leipzig, Germany

Application of the regional spectral cloud microphysics model COSMO-SPECS for sensitivity studies in real mixed-phase cloud scenarios

Within mixed phase clouds several microphysical processes exchange water between the three compartments vapor, liquid phase (cloud and rain droplets) and ice phase (ice and snow crystals). The SPECtral bin cloud microphysicS model SPECS was developed to simulate cloud processes using fixed-bin size distributions of aerosol particles and of liquid and frozen hydrometeors. It was implemented in the numerical weather prediction model COSMO, thereby substituting the original bulk one- or two-moment microphysics. Furthermore, an additional INP spectrum is introduced, which better enables the future coupling to INP diagnosed from aerosol chemistry transport model simulations. The model framework COSMO-SPECS was applied for 3D high-resolution real case studies on nested domains.
Detailed sensitivity studies on the effects of properties of the aerosol (CCN, INP, ice crystal shape) on the microphysical representation and evolution of the modelled clouds cases were conducted. The model simulations are compared against available remote sensing observations. Overall, the spectral cloud microphysics bring detailed insight into the microphysical processes taking place inside the modelled clouds. In particular the resulting formation of precipitation differs from the bulk model for the investigated cases. However, the simulations depend strongly on the given meteorological conditions provided by the outer driving model domains.

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2.3.9 Diego Villanueva

Eidgenössische Technische Hochschule Zürich (ETH), Zürich, Schweiz

Global patterns of cloud phase seasonality

Clouds between -42°C and 0°C may be in a phase of pure-liquid, pure-ice, or a mixture of both, affecting its radiative effect. However, the cloud phase variability is poorly understood, resulting in a high uncertainty in the climate warming projected by models. Here, we show that passive spaceborne retrievals of thick-extended clouds can help to better understand the variability of cloud phase. We find that for both the daily cloud phase and the seasonal phase frequency, the agreement among different retrieval algorithms increase for thick-extended clouds. For these clouds, we use 35 years of spaceborne retrievals to offer an estimation of the winter-summer and spring-fall contrast in cloud phase resolved globally. We suggest that the observed phase contrasts are likely associated to changes in deep convection over the subtropics, to aerosol ice nuclei over the mid-latitudes, and to isotherm height or sea-ice seasonality over high latitudes.

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2.3.10 Huiying Zhang

Huiying Zhang[1], Xia Li[2], Fabiola Ramelli[1], Robert O. David[3], Alexander Binder[4,5], Julie Pasquier[1], Trude Storelvmo[3], Ulrike Lohmann[1] and Jan Henneberger[1]

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[2] Institute for Machine Learning, ETH Zurich, Switzerland
[3] Department of Geosciences, University of Oslo, Norway
[4] Department of Informatics, University of Oslo, Norway
[5] Singapore Institute of Technology, Singapore, Singapore

Advancements in Ice Crystal Classification: A Multi-Label Approach with Rotated Object Detection

Ice crystals significantly impact cloud optical properties and precipitation formation, as their shape influences their radiative properties, diffusional growth rate, fall speed, and collision efficiency. Ambient conditions like temperature and humidity determine the basic habit of ice crystals, but microphysical processes like riming and aggregation can further shape them, leading to a diverse range of shapes. However, existing classification algorithms have limitations in assigning multiple labels to a single ice crystal, such as a rimed column, or classifying the components of an aggregated ice crystal.

To address these limitations, this study proposes a new multi-label classification scheme that considers both basic habits and physical processes that lead to the observed ice crystal shape. This study introduces a rotated object detection algorithm that classifies each component of an aggregated ice crystal individually, including both basic habit and physical processes. The algorithm was trained on 18,864 holographic ice crystal images and tested on 14,490 images captured during the NASCENT campaign in Ny-Alesund, Svalbard, from November 2019 and April 2020 respectively.

The algorithm offers an accuracy of 86.42% for basic habits and 81.64% for microphysical processes. Additionally, the algorithm shows a better generalization ability to predict ice crystal shapes in new datasets than traditional deep learning algorithms. Furthermore, it's worth noting that this algorithm can be used on any ice crystal image from other instruments, making it versatile for researchers. This flexibility may allow for more comprehensive and accurate data analysis by enabling the classification of ice crystals from a wider range of sources. The study results provide a deeper understanding of ice crystal shapes, leading to better estimates of ice crystal mass, fall velocity, and radiative properties, which can improve precipitation and radiation estimates, contributing to advances in weather forecasting and climate research.

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2.3.11 Britta Schäfer

Britta Schäfer[1], Robert Oscar David[1], Stian Dammann[1], Trude Storelvmo[1]

[1] University of Oslo, Department of Geosciences, Section for Meteorology and Oceanography

Modeling case studies of ice production in Arctic mixed-phase clouds

In common weather and climate models rime-splintering is the only included secondary ice production process. In addition, assumed concentrations of cloud condensation nuclei or cloud droplet number as well as of ice-nucleating particle are higher in standard models than for Arctic environments. This can lead to a misrepresentation of phase distribution in and precipitation from Arctic mixed-phase clouds.

During the Ny-Ålesund Aerosol Cloud Experiment (NASCENT) a holographic probe mounted on a tethered balloon took in-situ measurements of ice crystal and cloud droplet number and mass concentrations in Svalbard, Norway, during fall 2019 and spring 2020. In this study, we use the Weather Research and Forecasting (WRF) model to simulate selected case studies from this campaign in a high vertical and spatial resolution. We test the performance of different microphysical parametrizations and apply a new state-of-the-art secondary ice parametrization. We find that agreement with observations highly depends on the prescribed cloud condensation nuclei/cloud droplet and ice nucleating particle concentration. For a case with a lot of observed secondary ice production modeled ice crystal concentrations stay below the measured values even after adding new secondary ice processes to the model unless the number of splinters from rime-splintering events is increased.

In addition to sensitivity studies regarding microphysical parametrizations and the direct comparison with observations from the balloon, we analyze the spatial variability of cloud phase and its dependence on different meteorological parameters.

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2.3.12 Luisa Ickes

Luisa Ickes[1], Hannah Frostenberg[1], André Welti[2], Julien Savre[3], Erik S. Thomson[4]

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[2] Finnish Meteorological Institute, Finnland
[3] Ludwig-Maximilians-Universität, Munich, Germany
[4] University of Gothenburg, Gothenburg, Sweden

Including variability of INP concentrations when modelling mixed-phase clouds – lessons learned from a new conceptual approach to ice nucleation

Mixed-phase clouds often contain both ice and water and the right ratio between these two phases is difficult to simulate right in models. This is due to the high sensitivity to microphysical processes, which can either sustain or break down the unstable mixed-phase state, and uncertainties connected to the parameterization schemes describing these microphysical processes. One example is the parameterization of the influence of aerosol particles on the mixed-phase clouds, which can act as ice nucleating particle (INP).
INP concentrations can spread over several orders of magnitude at any given temperature. This variability is rarely accounted for in heterogeneous ice nucleation parameterizations. Here, we present a conceptual approach how to describe heterogeneous ice nucleation including this variability (and randomness connected to it) and present our lessons learned from using this parameterization scheme in a large-eddy simulation of an Arctic stratocumulus. We find that it leads to reasonable ice masses in the cloud and might be a solution for regions where aerosol information is not abundant or models that cannot capture a variety of aerosol particles. The scheme is sensitive to the median of the frequency distribution and highly sensitive to the standard deviation of the distribution. Generally, larger probability to draw high INP concentrations leads to substantially more ice in the simulated cloud. We expose inherent challenges to introducing such a parameterization and explore possible solutions and potential developments.

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2.3.13 Akinola Oluseyi E. (cancelled)

Obafemi Awolowo University (OAU), Ile-Ife, Nigeria

Role of Ice Hydrometeors Composition in a WRF-Simulated Convective Rainfall over West Africa.

During the West Africa Monsoon (WAM), majority ($\sim$ 80%) of the rainfall are produced by mesoscale convective systems that are of mixed-phase cloud in nature. However, there is a need to identify the role of ice hydrometeors composition (water droplets and ice crystals) in a mixed-phase cloud in other to be able to improve the forecasting of such rainfall using an already defined microphysical schemes in a mesoscale model like WRF. In this study, two observed convective rainfall events have been simulated using different bulk cloud microphysical schemes with varying degree of complexities of water and ice hydrometeors.

Results obtained shows that microphysical scheme that contains both less dense snow ice particle and dense graupel dense ice particle produced surface rainfall that are comparable to TRMM data used for validation in both events. Furthermore, vertical profile analysis of mass mixing ratios of the difference hydrometeors evaluated shows a greater mass of snow ice particles than other types of particles. A pressure-time plot of the differences between simulated air temperature and water vapor of the microphysical schemes shows that it simulated higher air temperature needed and the water vapor at the mid- and upper-troposphere.

The study concluded that both the dense ice particle (e.g. graupel) and less dense ice particle (e.g. snow) bulk microphysical schemes can both be used for forecasting heavy rainfall events that are produced by the convective system over the study area.

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2.3.14 Ong Chia Rui

University of Tokyo, Tokyo, Japan

Responses of Arctic mixed-phase clouds observed in the M-PACE and SHEBA campaigns to parameterized ice particle shape using the SCALE-AMPS model

We explore sensitivities of cloud microphysical properties to dominant ice particle shape (dendrites, plates, columns, or spheres) using the SCALE-AMPS large-eddy simulation model. AMPS is a bin microphysics scheme that predicts particle shapes based on the Inherent Growth Ratio (IGR) of spheroids, which determines vapor depositional growth rates along the a- and c-axes, and the rimed and aggregate mass fractions. We examine the impacts of various IGR values on simulations of clouds observed during the M-PACE and SHEBA experiments. Under M-PACE (SHEBA) conditions, LWP varies between 230 (6.7) and 49 (1.1) g m^{-2}, and the ice water path (IWP) varies between 3 (0.03) and 40 (0.12) g m^{-2} depending on ice shapes. The lowest LWP and highest IWP are obtained when columnar particles dominate because their low terminal velocities and large capacitance and collisional area result in large vapor deposition and riming rates whereas the highest LWP and lowest IWP are obtained when spherical particles dominate because their vapor deposition and riming rates are low. Because ice particle shape significantly influences simulated Arctic mixed-phase clouds, reliable simulations require accurate representation of ice shape for which accurate IGR values estimated under various atmospheric conditions are needed. Finally, comparisons between simulation results and M-PACE observations show that the size distribution larger than 2000 µm is better reproduced when the increase in rimed mass that causes ice particles become spherical is suppressed. However, the LWP becomes much lower than observations because water droplets are depleted by riming of these large ice crystals ($>$ 2000 µm) with high riming efficiency. This interesting result indicates that shape change due to riming and the hexagonal ice shape assumed in the model are insufficient for accurate simulations of heavy-riming mixed-phase clouds.

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2.4 Laboratory studies

2.4.1 Miklós Szakall (invited)

Johannes Gutenberg-Universität Mainz, IPA, Mainz, Germany

Wind tunnel studies on microphysical processes in mixed phase clouds

The Mainz vertical wind tunnel is a one-of-a-kind facility dedicated to the study of microphysical processes of individual cloud and precipitation particles. In this presentation, I will provide an overview on the key experimental findings obtained from our wind tunnel measurements over the past four decades. The focus of this overview will be on elucidating the phase change processes that occur throughout the life cycle of the hydrometeors in mixed phase clouds.

First, the ice nucleation will be discussed and experiments related to immersion and contact freezing will be introduced. Regarding growth mechanisms, emphasis will be placed on the results on riming of graupel. Another ice generation process to be discussed will be the fragmentation that occurs as a result of collisions between ice particles. This process is considered as an important secondary ice production mechanism, and therefore might play a significant role in understanding the complete life cycle of ice particles.

An emerging area of interest, particularly in the context of a changing climate, is the microphysics of hail, graupel, and snow. Therefore, the final part of the talk will address experiments focused on their aerodynamics, ventilation, and melting properties.

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3 Ice multiplication processes (SIP)

3.1 Alexei Kiselev (invited)

Karlsruher Institut für Technologie (KIT), Karlsruhe, Germany

Solving the Atmospheric Ice Multiplication Puzzle: Lab, Cloud, or Model?

Ice crystals in clouds can significantly affect weather and climate. However, the formation of ice crystals, especially in mixed-phase clouds, is still not well understood. At sub-zero temperatures, the freezing of supercooled water drops is facilitated by the presence of ice-nucleating particles (INPs). Nonetheless, INPs are relatively rare in the atmosphere, typically occurring in number concentrations well below one per liter of air at -10°C. In contrast, numerous observations indicate ice crystal number concentrations that are orders of magnitude higher than what is predicted based on INP concentrations, observed in a variety of clouds worldwide. The observed enhancement of ice crystal number concentrations is believed to be explained by ice multiplication (IM) processes, which involve the formation of ice from pre-existing ice crystals. However, the diverse mechanisms of ice multiplication and their relative contributions to cloud glaciation are not yet fully characterized, preventing the reliable representation of ice formation processes in cloud models across all scales. In this introductory lecture, I will review past and recent laboratory efforts aimed at understanding and characterizing various ice multiplication mechanisms, including rime-splintering, droplet fragmentation upon freezing, and ice-droplet collisions, among others. I will demonstrate the necessity to revise the current understanding of the well-established IM mechanisms, based on very recent experimental and in-situ cloud observations. Additionally, I will emphasize the importance of combining research from the fields of in-situ cloud observations, remote sensing, and modeling, showcasing recent contributions from leading scientists. This interdisciplinary approach is crucial for gaining a comprehensive understanding of atmospheric ice multiplication.

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3.2 Sachin Patade

Lund University, Lund, Sweden

The influence of multiple groups of biological ice nucleating particles on microphysical properties of mixed-phase clouds observed during MC3E

A new empirical parameterization (EP) for multiple groups of primary biological aerosol particles (PBAPs) is implemented in the aerosol–cloud model (AC) to investigate their roles as ice nucleating particles (INPs). The EP describes the heterogeneous ice nucleation by (1) fungal spores, (2) bacteria, (3) pollen, (4) detritus of plants, animals, and viruses, and (5) algae. Each group includes fragments from the originally emitted particles. A high-resolution simulation of a midlatitude mesoscale squall line by AC is validated against airborne and ground observations.

Sensitivity tests are carried out by varying the initial vertical profiles of the loadings of individual PBAP groups. The resulting changes in warm and ice cloud microphysical parameters are investigated. The changes in warm microphysical parameters, including liquid water content and cloud droplet number concentration, are minimal (<10 %). Overall, PBAPs have little effect on the ice number concentration (<6 %) in the convective region. In the stratiform region, increasing the initial PBAP loadings by a factor of 1000 resulted in less than 40 % change in ice number concentrations. The total ice concentration is mostly controlled by various mechanisms of secondary ice production (SIP). However, when SIP is intentionally shut down in sensitivity tests, increasing the PBAP loading by a factor of 100 has an effect of less than 3 % on the ice phase. Further sensitivity tests revealed that PBAPs have little effect on surface precipitation and on the shortwave and longwave flux (<4 %) for a 100-fold perturbation in PBAPs.

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3.3 Zane Dedekind

Zane Dedekind[1,2], Ulrike Proske[1], Jacopo Grazioli[3], David Neubauer[1], Phil Austin[2], Sylvaine Ferrachat[1], and Ulrike Lohmann[1]

[1] Institute of Atmospheric and Climate Science, ETH Zurich, Switzerland
[2] University of British Columbia, Vancouver, British Columbia, Canada
[3] Environmental Remote Sensing Laboratory (LTE), École Polytechnique Fédérale de Lausanne (EPFL, Lausanne, Switzerland

Secondary ice production: Assessing case studies involving strong vertical wind shear and the seeder-feeder effect

Numerical weather prediction simulations that incorporate collisional breakup have been shown to improve ice crystal concentrations in mixed-phase clouds (MPCs) and surface precipitation. Collisional breakup happens when two frozen hydrometeors of different densities collide, causing shattering. This phenomenon was included in the Consortium for Small-scale Modeling (COSMO) model at a 1 km horizontal grid spacing and evaluated in two case studies in the Swiss Alps.
In the first case study, the vertical wind shear causing turbulence increased the interaction between ice particles and led to enhanced collisional breakup. An X-band weather radar observed intense dual-polarization Doppler signatures with strong vertical wind shear during a high-intensity precipitation event. Collisional-breakup simulations reproduced measured horizontal reflectivity and ground-based observations of hydrometeor number concentration more accurately. During the afternoon, the mean vertical wind shear strengthened substantially within the region favorable for SIP resulting in enhanced SIP. The mutual information between the SIP rate and vertical wind shear suggests that SIP is best predicted by vertical wind shear.
In the seeder-feeder process, ice particles that sediment into a lower cloud from an upper cloud (external seeder-feeder process) or into the mixed-phase region of a deep cloud from cirrus levels (internal seeder-feeder) can amplify cloud glaciation and enhance surface precipitation. In a second case study, it was found that 47.6% of all observed clouds are categorized as multi-layered clouds, in which the external seeder-feeder process occurred in 10.3% of these clouds. Inhibiting the external seeder-feeder process led to a reduction in average surface precipitation and riming rate. Further reductions were seen when ice graupel collisions were allowed. Inhibiting the internal seeder-feeder process resulted in a deamplification of cloud glaciation and a reduction in surface precipitation.
The results indicate that collisional breakup plays an important role in simulating the cloud properties of MPCs. The simulations provide more accurate predictions of hydrometeor concentrations and radar reflectivity, which can be useful for weather forecasting.

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4 Ice nucleating particles

4.1 Heike Wex (invited)

Leibniz-Institut für Troposphärenforschung (TROPOS), Leipzig, Germany

Research on atmospheric INP: Where are we and how can we make good use of our knowledge

In this presentation and subsequent discussion round, it will be all about ice nucleating particles, INP, which are at the formation of primary ice in mixed phase clouds but also can play a role in cirrus clouds. In the presentation, after some words on the historical development of our knowledge on INP, a broader range of issues and differing directions into which research on INP is currently done will be introduced. After opening up the broad field around (atmospheric) INP in the presentation, a discussion should follow, all focusing on INP: Are there research goals which are more important than others, why are they more important, and does that maybe point towards directions which should preferentially be examined in our research?

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4.2 Christof Beer

C. Beer, J. Hendricks, and M. Righi

Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany

Quantifying the global distribution of ice-nucleating particles and their climate impacts from model simulations with MADE3 in EMAC

Ice-nucleating particles (INPs) can exert important influences on the formation and the microphysical properties of cirrus clouds [1, 2]. However, the knowledge about the atmospheric distribution of INPs is still limited and consequently the understanding of their climate impacts is highly uncertain. We perform model simulations with a global aerosol-climate model coupled to a two-moment cloud microphysical scheme and a parametrization for aerosol-induced ice formation in cirrus clouds and present a global climatology of INPs in the cirrus regime [3]. This novel INP climatology comprises, in addition to the broadly considered mineral dust and soot INPs, also crystalline ammonium sulfate and glassy organic particles. The simulated INP number concentrations range from about 1 to 100 L^{-1} and agree well with in-situ observations and other global model studies. While glassy organic INP concentrations are mostly low in the cirrus regime, our model results show large ammonium sulfate INP concentrations. By coupling the different INP-types to the microphysical cirrus cloud scheme, their ice nucleation potential under cirrus conditions is analyzed, considering possible competition mechanisms between different INPs. To quantify the impact of the INPs on the radiative forcing of cirrus clouds we compare a simulation with all different INP-types and a simulation with only homogeneous freezing. This results in a radiative forcing of -28 and -55 mW m^{-2}, assuming a lower and an increased ice-nucleating potential of INPs. While the simulated impact of glassy organic INPs is mostly small and not significant, ammonium sulfate INPs introduce a considerable radiative forcing, which is nearly as large as the combined effect of mineral dust and soot INPs. The INP-cirrus effect due to anthropogenic INPs, considering the difference between present-day and preindustrial conditions, amounts to -29 mW m^{-2}.

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4.3 Mark D. Tarn

Mark D. Tarn[1], Sarah L. Barr[1], Katherine H. Bastin[1], Kathleen A. Thompson[1], Polly B. Foster[1], Sam J. Clarke[1], Joseph Robinson[1], James B. McQuaid[1], Zongbo Shi[2] and Benjamin J. Murray[1]

[1] School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK
[2] School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK

Ice-nucleating particles in the Labrador Sea region

As the Earth warms, it is important to understand how a change in the ice:water ratio in mixed-phase clouds influences the cloud-phase feedback, and in turn how INPs, which trigger the freezing of liquid cloud droplets, will regulate this process. To achieve this, it is necessary to identify the types, sources, and concentrations of INPs to determine their contribution. We undertook two INP measurement campaigns in the Labrador Sea region, which features clouds that are susceptible to the effects of INPs, in 2022: (i) a cruise on the RRS Discovery, as part of a joint SEANA/M-Phase project in May-June, and (ii) a flight campaign on the FAAM aircraft as part of the M-Phase project in October-November. Preliminary results from the ship cruise suggest that high INP concentrations during the campaign correlated with air masses that had passed over the coast of Greenland, while low concentrations were associated with air masses that had passed over the sea or the sea ice. These results suggest a high-latitude source of INPs not currently accounted for in models, the study of which could be crucial in understanding their influence on clouds in a changing climate. Preliminary results from the flight campaign results suggest highly reproducible INP concentrations during cold air outbreak (CAO) events, with highly variable concentrations outside of CAOs. Further processing of the campaign data will allow the sources and concentrations of INPs in the Labrador Sea region to be established, and their effect on shallow mixed-phase clouds in the mid-to-high latitudes explored.

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4.4 Polly Foster

Polly B. Foster[1], Mark D. Tarn[1], Loic Coudron[2], Ian Johnston[2], Sally A. Peyman[3], Benjamin J. Murray[1]

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[2] School of Physics, Engineering, and Computer Science, University of Hertfordshire, AL10 9AB, UK
[3] School of Physics and Astronomy, University of Leeds, LS2 9JT, UK

The Use of Electrostatic Precipitation for Collection of Atmospheric Ice-Nucleating Particles

Ice-nucleating particles (INPs) are a key modulator of ice formation in clouds via the freezing of supercooled clouds droplets, leading to enhanced precipitation and reduced cloud lifetime, consequently impacting cloud radiative properties. The rarest and least understood sources of INPs are those causing freezing at the warmest temperatures, commonly of biogenic origin, which can be dominated by mineral dust INPs that exist at higher concentrations in ambient air samples. INP concentrations are quantified using droplet freezing assays, whereby droplets are produced of an aqueous suspension of atmospheric aerosol, known as the wash volume, and subsequently frozen. A smaller wash volume, as well as smaller droplets, increases the likelihood of rare INPs being detected in the droplet freezing assay. Electrostatic precipitation of particles that can be collected off a hydrophobic slide into a highly concentrated sample has been explored as a novel application to atmospheric INP collection. The preliminary results for the use of an aerosol sampler based on electrostatic precipitation for collection of atmospheric INPs, compared to a traditional filter based collection method, indicate consistency at lower INP activation temperatures, whilst extending measurements into the warmer temperature range of rare INP types. Future work will see the ESP used in conjunction with a microfluidic INP analysis system to quantify and identify agricultural sources of INPs.

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4.5 Erin Raif

Erin Raif[1], Sarah Barr[1], Jim McQuaid[1], Mark Tarn[1], Steven Abel[2], Paul Barrett[2], Keith Bower[3], Paul Field[1,2], Ben Murray[1], Ken Carslaw[1]

[1] Institute for Climate and Atmospheric Science, University of Leeds, Leeds, UK.
[2] Met Office, Exeter, UK.
[3] Department of Earth and Environmental Science, University of Manchester, Manchester, UK.

Ice-nucleating particles in springtime cold-air outbreaks are associated with Arctic haze

The global variation of ice-nucleating particle (INP) concentrations is an important modulator of the cloud-phase feedback, where the albedo of mixed-phase clouds increases in a warming climate. Shallow cloud systems such as those observed in mid- to high-latitude cold-air outbreaks (CAOs) are particularly important for cloud-phase feedbacks and highly sensitive to INPs. However, climate models poorly constrain INP concentrations and sources in these regions.

To investigate the sources and concentrations of INPs in CAOs, we made airborne measurements over the Norwegian and Barents Seas as part of the spring 2022 Arctic Cold Air Outbreak field campaign. Throughout the campaign, INP concentrations were comparable to the highest previously observed Arctic INP measurements and significantly higher than those reported in remote Southern Ocean regions.

Analysis of aerosol-size data to obtain the active site density of the INP samples suggests that sea spray is unlikely to be the dominant INP source and that there is a strong biological component to the INP population. Meteorological conditions suggest that INPs are most likely to be associated with aged aerosol in the Arctic haze that has undergone long-range transport from lower latitude regions rather than local sources.

As a next step, we plan to model CAOs in climate simulations to assess the strength of the cloud-phase feedback. We plan to use INP parametrisations based on these measurements and perform sensitivity analyses to test the impact of changing INP concentrations on CAO development, cloud albedo and feedback parameter.

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4.6 Cuiqi Zhang

C. Zhang[1], Z. A. Kanji[1]

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Development of a new instrument for continuous monitoring of ice nucleating particles

Ice crystals occurring in mixed-phase clouds play a vital role in global precipitation and energy balance because of the unstable equilibrium between coexistent liquid droplets and ice crystals, which affects cloud lifetime and radiative properties, as well as precipitation formation. Satellite observations proved that immersion freezing, i.e., ice formation on ice nucleating particles (INPs) immersed within aqueous droplets, is the dominant ice nucleation (IN) pathway in mixed-phase clouds. However, aerosol-cloud interactions have been a persistent source of uncertainty in determining anthropogenic forcing, climate sensitivity and the climate effects of aerosol.

Field observation and characterization of atmospheric aerosols could provide first-hand input data for global climate models and lay the foundation of accurately quantifying the indirect climate effect of aerosols. Presently, the data acquisition for most online INP counters still requires a human operator. To address this restriction, we are developing "HINC-Auto", a fully automated online INP counter, by adapting an existing custom-built instrument, the Horizontal Ice Nucleation Chamber (HINC). HINC has successfully been used to detect INP concentrations during numerous field campaigns since 2014. HINC-Auto has been successfully collecting data at the High Altitude Research Station Jungfraujoch (JFJ, 3580 m a.s.l., 46°33' N, 7°59' E) for one year between February 2020 to March 2021. After refurbishment, two HINC-Autos have currently been respectively deployed at JFJ and Swiss midland site Payerne (PAY, 491 m a.s.l., 46°48' N, 6°56' E).

The resulting continuous and more detailed temporal analysis of ambient INP concentrations allows observing repeated meteorological episodes compared to previous singular events detected during a campaign. In addition, it enables the comparison with lower time resolved parameters such as mass and concentration of PM10 species.

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4.7 Florian Reyzek

Florian Reyzek[1], Teresa M. Seifried[1,2], Paul Bieber[1,2], and Hinrich Grothe[1]

[1] Institute of Materials Chemistry, TU Wien, Vienna, 1060, Austria
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Exploring the role of silver birch and scots pine as atmospheric INM sources

Silver birch (*Betula pendula*) and Scots pine (*Pinus sylvestris*) are prevalent tree species in the northern hemisphere, distributed across a wide range from Western Europe to Eastern Siberia. Past ice nucleation studies on birch trees identified them to have efficient ice-nucleating macromolecules (INMs) all over the surface.

In recent years, we focused on the INM distribution on the surface of Silver birch. We collected tissue samples (leaf, branch wood, bark), extracted the INMs from the intact surface, and found 10^5 to 10^{10} INMs per cm^2 Silver birch tissue surface. From the in-depth chemical analysis of Silver birch INMs, we conclude that the INMs are likely large aggregates with polysaccharide or proteinaceous subunits.

More recently, we conducted a similar study with Scots pine. We found that the INM concentrations range from 10^5 to 10^8 INMs per cm^2 Scots pine tissue surface.

In addition, we collected rain samples underneath both Silver birch and Scots pines and found them to contain INMs with similar freezing onset temperatures as the surface extracts. Thus, we show that INMs are easily released from the trees' surface.

Summarizing our results from the past years, we extrapolated our results to estimate that one square meter of birch stand can release 10^{13} to 10^{15} INMs, and one square meter of Scots pine stand can release about 10^9 to 10^{12} INMs. This highlights Silver birch and Scots pines as massive INM reservoirs, suggesting that forests with abundant birch and pine trees should be considered significant sources of atmospheric INMs. Our chemical analysis will further help to identify these potentially highly abundant INMs in various field measurements.

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4.8 Sylwester Arabas

Sylwester Arabas et al.

AGH University of Science and Technology, Kraków, Poland

Immersion freezing in particle-based aerosol-cloud microphysics models: comparing singular and time-dependent schemes

Probabilistic particle-based cloud microphysics models open up possibilities of untangling the complexity of aerosol-cloud-precipitation interactions through particle-level model formulation. As a result, processes such as droplet coalescence, graupel growth through riming, formation of snow aggregates and aerosol scavenging can all be represented by a single Monte-Carlo "coagulator" within frameworks such as Large Eddy Simulations. Moreover, by design, the particle-based microphysics models capture the aerosol (including CCN and INP) reservoir dynamics. In this study, we focus on comparison of two contrasting representations of the immersion freezing process for particle-based aerosol-cloud microphysics models: a singular and a time-dependent scheme. In both cases, we use a probabilistic approach in which the particle attribute space is randomly sampled at initialisation. For the singular model, the key particle attribute is the freezing temperature with its probability density function derived from the the ice nucleation active sites (INAS) parameterisation. For the time-dependent scheme, we use the water activity based immersion freezing model (ABIFM) with parameters derived from the very same laboratory measurements as INAS. Employing idealised box-model and prescribed-flow simulations, we depict the tradeoffs of using the singular model, and highlight the robustness of the time-dependent scheme.

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5 Cloud instrumentation, Cloud probe processing techniques

5.1 Veronika Ettrichraetz

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Complexity of Snowflakes - A Case Study of the Benefits of Synergy between a snowfall camera VISSS, 94 GHz Radar, and PAMTRA

Snowfall is a crucial component of the water cycle and the radiation balance, yet the micro- and macrophysical properties of snow are still not well understood. To improve remote sensing methods and weather and climate models, further investigations are needed. In the SAIL-CORSIP measurement campaign conducted in Mount Butted-Crest (Colorado) between early November and late May of the 2022-2023 season, we used a snowfall camera (VISSS) and a polarimetric W-band radar system to measure snowfall. The VISSS allowed us to observe particle size, number, and shape, which were compared to the polarimetric variables (reflectivity, differential reflectivity, differential phase shift, and ratio of horizontal and vertical signals) obtained from the radar. Furthermore, we aim to improve the Passive and Active Microwave radiative TRAnsfer tool (PAMTRA) by incorporating these measurements. In this study, we focused on the high complexity dendrites and low complexity rimed graupel, and compared the results obtained from our two instruments. Our results show that the measurements obtained from the two different instruments are complementary, and clear differences were observed depending on the particle complexity. These findings demonstrate the benefits of the synergy between the snowfall camera, radar system, and PAMTRA in understanding the complexity of snowflakes.

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5.2 János Stenszky

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Improving the Balloon-borne Ice Cloud particle Imager (B-ICI)

Atmospheric constituents, such as aerosols and clouds, greatly affect the radiative properties of the atmosphere. Clouds play a substantial role in this radiative balance. To better understand the contribution of cirrus clouds improved modelling and in-situ observations are needed.
For further improving current climate-modelling parameters, accurate parameterization of these clouds are required. From in-situ measurements, the size distribution of cirrus ice particles, their concentration and shape parameters can be determined. This can be achieved with the iBalloon-borne Ice Cloud particle Imager (B-ICI). Campaigns done with the B-ICI and resulting parameetrizations have contributed to more accurate characterization of cirrus clouds.
The B-ICI is collecting and imaging ice particles with a pixel resolution of 1,65 µm/pixel. With detailed image analysis at this accuracy particles > 20µm can be distinguished, dimensions and concentration can be derived, and particles can be sorted according to their shape. An improved version of B-ICI is currently being developed. This new version of the instrument is primarily improving image quality to enable easier and more automated image processing. Secondarily, changes in the design will reduce the weight of the instrument and simplify the method for sampling of ice particles. A more light-weight instrument will allow adding other sensors. In particular, an optical particle counter to measure aerosol and small ice particles will be added to the B-ICI. This addition of an optical particle counter will result in more accurate size distributions in addition of providing complementary aerosol measurements. In this paper, we will highlight these changes and improvements in the B-ICI setup.

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Workshop 'Clouds containing Ice Particles'

Joh. Gutenberg Univ. Mainz, 'Alte Mensa', 23 - 26 July, 2023

List of Contributions

(* invited)

Presenter	Institution	Title	email
Cirrus clouds: in-situ measurements			
* Eric Jensen	NOAA Boulder	What have we learned from in situ measurements of cirrus: physical properties and processes	eric.jensen@noaa.gov
Martina Krämer	FZ Jülich	Occurrence patterns of ice cloud particles sizes	m.kraemer@fz-juelich.de
Yun Li	FZ Jülich	Observational evidence of contrail cirrus in slightly ice-subsaturation	yun.li@fz-juelich.de
Nils Brast	JGU Mainz	3D climatology of ice supersaturated regions over the North Atlantic	nibrast@uni-mainz.de
Philipp Reutter	JGU Mainz	–	preutter@uni-mainz.de
Elena de la Torre Castro	DLR Oberpf.hofen	Differences in microphysical properties of cirrus at high and mid-latitudes	Elena.delaTorreCastro@dlr.de
Rachel Atlas	LMD IPSL	Detecting gravity waves and turbulence within airborne lidar images of cirrus clouds in the tropical troposphere layer	rachel.atlas@lmd.ipsl.fr
Andrew Dzambo	Univ. Oklahoma	Synergizing in-situ cloud probe measurements and radar reflectivity curtains for diagnosing in-cloud turbulence and gravity wave activity	dzamboam@ou.edu
Cirrus clouds: remote sensing observations			
* Odran Sourdeval	University of Lille	Understanding ice clouds from satellite observations	odran.sourdeval@univ-lille.fr
Athulya Saiprakash	University of Lille	Investigating ice cloud formation mechanisms from satellite observations and Lagrangian transport and microphysical models	athulya.saiprakash@univ-lille.fr
Sajedeh Marjani	Uni. Leipzig	–	sajedeh.marjani@uni-leipzig.de
Johannes Röttenbacher	Uni. Leipzig	Quantification of the Radiative Effect of Arctic Cirrus by Airborne Measurements - A Case Study	jr17zevo@studserv.uni-leipzig.de
Silke Gross	DLR Oberpf.hofen	Investigating an aviation induced indirect aerosol effect on cirrus clouds using airborne and spaceborne lidar measurement	Silke.Gross@dlr.de
Georgios Dekoutsidis	DLR Oberpf.hofen	The effects of warm air intrusions in the high arctic on cirrus clouds	Georgios.Dekoutsidis@dlr.de
Anthony Baran	Met Office Exeter	Testing Model Consistency using the Boundary Element Method for Computing Backscattering Properties of Complex Ice Crystals at Multiple Frequencies Using Radar Reflectivity Data from the IMPACTS Campaign	anthony.baran@metoffice.gov.uk
Kai Jeggle	ETH Zürich	Identification of cirrus formation regimes using cluster analysis of back trajectories and satellite data	kai.jeggle@env.ethz.ch
David Mitchell	DRI Reno	Global Estimates of the Fraction of Cirrus Clouds affected by Homogeneous Ice Nucleation	David.Mitchell@dri.edu

Presenter	Institution	Title	email
Cirrus clouds: theory and simulations			
* Blaž Gasparini	Uni. Wien	It's time to clear up uncertainties related to tropical cirrus clouds	blaz.gasparini@univie.ac.at
* Klaus Gierens	DLR Oberpf.hofen	Cirrus clouds, ice supersaturation, and their dynamical background	Klaus.Gierens@dlr.de
Blaž Gasparini	Uni. Wien	Simple microphysical changes improve cirrus representation in cloud resolving models	blaz.gasparini@univie.ac.at
Peter Spichtinger	JGU Mainz	Ice clouds as nonlinear oscillators - a treatment using dynamical systems theory	spichtin@uni-mainz.de
Hannah Bergner	JGU Mainz	Gravity waves and ice clouds – Interaction of dynamics and microphysics using a modelling approach	h.bergner@uni-mainz.de
Partick Konjari	FZ Jülich	–	p.konjari@fz-juelich.de
Stamen Dolaptchiev	Univ. Frankfurt	Gravity wave spectra interacting with ice clouds	dolaptchiev@iau.uni-frankfurt.de
Alena Kosareva	Univ. Frankfurt	Homogeneous nucleation of ice particles forced by gravity waves in ICON based on asymptotic solution	Kosareva@iau.uni-frankfurt.de
Dario Sperber	DLR Oberpf.hofen	Towards a more reliable forecast of ice supersaturation: Concept of a one-moment ice cloud scheme that avoids saturation adjustment	dario.sperber@dlr.de
Ulrike Burkhardt	DLR Oberpf.hofen	Changes in cirrus cloudiness due to contrail formation within cirrus	Ulrike.Burkhardt@dlr.de
Karol Corko	DLR Oberpf.hofen	Evaluation of the tropical upper tropospheric cloudiness simulated by the convection permitting DYAMOND models	Karol.Corko@dlr.de
Simon Unterstraßer	DLR Oberpf.hofen	Collection/Aggregation in a Lagrangian cloud microphysical model: Insights from column model applications	simon.unterstrasser@dlr.de
Jhaswantsing Purseed	CNRS, IPSL, Paris	Large Eddy Simulations of aerosol-cirrus interactions	purseed.jhaswantsing@ipsl.fr
Aurelien Podglajen	CNRS, Paris	Relationship between TTL cirrus and gravity waves: observations from a balloon-borne lidar and idealized numerical simulations	aurelien.podglajen@lmd.ipsl.fr
Tuule Müürsepp	ETH Zürich	Radiative heating profiles in different parts of cirrus clouds associated with extratropical cyclones	tuule.mueuersepp@env.ethz.ch
Anthony Baran	Met Office Exeter	A first consistent coupling between aerosol–ice interactions and radiation, and its impact in a high-resolution weather model	anthony.baran@metoffice.gov.uk
Edgardo Sepulveda Araya	Univ. Arizona, Tuscon	A Two-Fold Approach to Quantify Ice Cloud-Radiative Heating Rate Sensitivity to Cloud Optical, Macro and Microproperties	edgardo@arizona.edu
Sami Turbeville	Univ. Washington Seattle	How much does microphysics matter for simulating cirrus clouds?	smturbev@uw.edu

Presenter	Institution	Title	email
Mixed phase clouds: in-situ measurements			
* Greg McFarquhar	Univ. Oklahoma	In-Situ Measurements of Mixed-Phase Clouds: What is State of Art and What are Ongoing Challenges	mcfarq@ou.edu
Sam Clarke	Univ. Leeds	The M-Phase project – Overview and Regional Modelling Plans	S.J.Clarke@leeds.ac.uk
Andy Heymsfield	NCAR Boulder	cancelled	heyms1@ucar.edu
Jan Henneberger	ETH Zürich	Bridging the ice crystal growth knowledge gap by seeding supercooled stratus clouds with a UAV	jan.henneberger@env.ethz.ch
Simon Kirschler	DLR Oberpf.hofen	Initiation of the ice phase promotes precipitation in the western North-Atlantic Ocean	Simon.Kirschler@dlr.de
Nina Maherndl	Univ. Leipzig	Airborne observations of riming in arctic mixed-phase clouds during HALO-(AC)3	nina.maherndl@uni-leipzig.de
Jeffrey R. French	Univ. Wyoming Laramie	Airborne Observations of Super-cooled Drizzle, Secondary Ice Production, and Mixed Phase Clouds during WINTRE-MIX	jfrench@uwyo.edu
Chris Hohman	Univ. Wyoming Laramie	Simulation of Glaciogenic Cloud Seeding Case During SNOWIE	chohman@uwyo.edu
Mixed phase clouds: remote sensing observations			
Leonie von Terzi	Univ. München	Ice microphysical processes in the dendritic growth layer: can we close current knowledge gaps by combining novel cloud radar observations with Lagrangian Monte-Carlo particle modeling?	L.Terzi@physik.uni-muenchen.de
Anna Weber	Univ. München	Remote sensing of cloud thermodynamic phase from spectral and multi-angle polarimetric imaging	Weber.Ann@physik.uni-muenchen.de
Johanna Mayer	DLR Oberpf.hofen	A probabilistic approach to determine the thermodynamic cloud phase using passive satellites	Johanna.Mayer@dlr.de
Barbara Dietel	KIT Karlsruhe	The phase of midlevel and lowlevel clouds over the Southern Ocean and the Arctic Ocean	barbara.dietel@kit.edu

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Mixed phase clouds: theory and simulations			
* Anna Jaruga	Caltech Pasadena	The fundamentals of microphyics in mixed phase clouds	ajaruga@caltech.edu
* Anna Possner	Univ. Frankfurt	Importance of mixed-phase cloud processes for cloud dynamics and cloud radiative effects in the climate system	apossner@iau.uni-frankfurt.de
Tim Lüttmer	JGU Mainz	Cirrus in WCB outflow: in-situ versus liquid origin	tluettm@uni-mainz.de
Cornelis Schwenk	JGU Mainz	–	c.schwenk@uni-mainz.de
Theresa Kiszler	Univ. Köln	Studying the representation of macro- and microphysical cloud properties at Ny-Ålesund in ICON	tkiszler@uni-koeln.de
Alberto de Lozar	Deutscher Wetterdienst	Adjusting microphysical processes in observational space	Alberto.Lozar-de@dwd.de
Christoph Siewert	Deutscher Wetterdienst	The particle-based mixed-phase microphysics model McSnow	Christoph.Siewert@dwd.de
Gabriella Wallentin	KIT Karlsruhe	Arctic Mixed-phase Multilayer Clouds: A simulation study in search of cloud ice	gabriella.wallentin@kit.edu
Roland Schrödner	Tropos Leipzig	Application of the regional spectral cloud microphysics model COSMO-SPECS for sensitivity studies in real mixed-phase cloud scenarios	roland.schroedner@tropos.de
Diego Villanueva	ETH Zürich	Global patterns of cloud phase seasonality	diego.villanueva@env.ethz.ch
Zhang Huiying	ETH Zürich	Advancements in Ice Crystal Classification: A Multi-Label Approach with Rotated Object Detection	huiying.zhang@env.ethz.ch
Britta Schäfer	University of Oslo	Modeling case studies of ice production in Arctic mixed-phase clouds	britta.schafer@geo.uio.no
Luisa Ickes	Chalmers Göteborg	Including variability of INP concentrations when modelling mixed-phase clouds – lessons learned from a new conceptual approach to ice nucleation	luisa.ickes@chalmers.se
Akinola Oluseyi	OAU Ile-Ife, Nigeria	cancelled	akinolaoe@oauife.edu.ng
Thabo Makgoale	Univ. Arizona Tuscon	cancelled	temakgoale@arizona.edu
Chia Rui Ong	Univ. of Tokyo	Responses of Arctic mixed-phase clouds observed in the M-PACE and SHEBA campaigns to parameterized ice particle shape using the SCALE-AMPS model	ong.chiarui@eps.s.u-tokyo.ac.jp
Mixed phase clouds: laboratory studies			
* Miklós Szakall	JGU Mainz	Wind tunnel studies on microphysical processes in mixed phase clouds	szakall@uni-mainz.de
Sudha Yadav	JGU Mainz	–	syadav@uni-mainz.de

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Ice multiplication processes (SIP)			
* Alexei Kiselev	KIT Karlsruhe	Solving the Atmospheric Ice Multiplication Puzzle: Lab, Cloud, or Model?	alexei.kiselev@kit.edu
Sachin Patade	Lund University	The influence of multiple groups of biological ice nucleating particles on microphysical properties of mixed-phase clouds observed during MC3E	sachin.patade@nateko.lu.se
Zane Dedekind	Env. Canada, Montréal	Secondary ice production: Assessing case studies involving strong vertical wind shear and the seeder-feeder effect	Zane.Dedekind@ec.gc.ca
Ice nucleating particles			
* Heike Wex	Tropos Leipzig	Research on atmospheric INP: Where are we and how can we make good use of our knowledge	wex@tropos.de
Christof Beer	DLR Oberpf.hofen	Quantifying the global distribution of ice-nucleating particles and their climate impacts from model simulations with MADE3 in EMAC	Christof.Beer@dlr.de
Mark D. Tarn	Univ. Leeds	Ice-nucleating particles in the Labrador Sea region	m.d.tarn@leeds.ac.uk
Polly Foster	Univ. Leeds	The Use of Electrostatic Precipitation for Collection of Atmospheric Ice-Nucleating Particles	p.foster1@leeds.ac.uk
Erin Raif	Univ. Leeds	Ice-nucleating particles in springtime cold-air outbreaks are associated with Arctic haze	eeenr@leeds.ac.uk
Cuiqi Zhang	ETH Zürich	Development of a new instrument for continuous monitoring of ice nucleating particles	cuiqi.zhang@env.ethz.ch
Florian Reyzek	TU Wien	Exploring the role of silver birch and scots pine as atmospheric INM sources	florian.reyzek@tuwien.ac.at
Sylwester Arabas	AGH Univ. Kraków	Immersion freezing in particle-based aerosol-cloud microphysics models: comparing singular and time-dependent schemes	sylwester.arabas@uj.edu.pl
Cloud instrumentation, Cloud probe processing techniques			
Veronika Ettrichraetz	Univ. Leipzig	Complexity of Snowflakes - A Case Study of the Benefits of Synergy between a snowfall camera VISSS, 94GHz Radar, and PAMTRA	veronika.ettrichraetz@uni-leipzig.de
János Stenszky	LTU Kiruna	Improving the Balloon-borne Ice Cloud particle Imager (B-ICI)	janos.stenszky@ltu.se
Saurabh Patil	Univ. of Oklahoma	The processing of cloud in-situ observations from ESCAPE field campaign using UIOOPS	saurabh@ou.edu