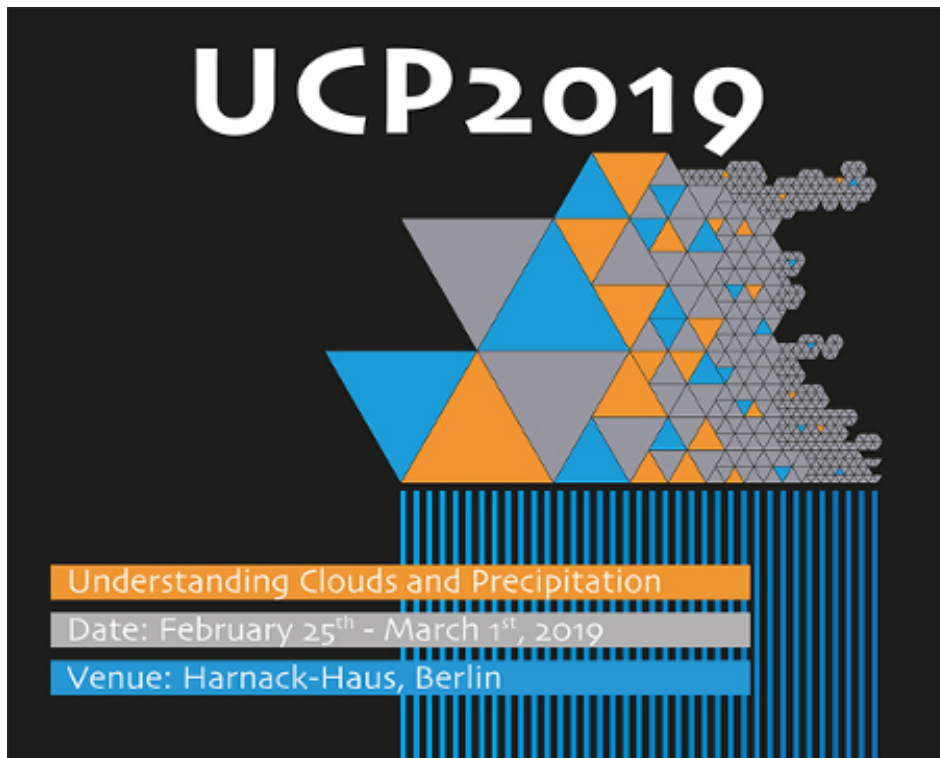


# UCP2019 - Understanding Clouds and Precipitation

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## Book of Abstracts



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## Welcome by UCP2019 conference committee

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## Welcome note by the Federal Ministry of Education and Research

Morning session: Topic II / 320

### Insights into marine boundary-layer clouds and aerosols from recent NE Pacific and Southern Ocean field campaigns

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Marine boundary layer clouds and their response to greenhouse gas perturbations and natural and anthropogenic aerosols remain a central challenge of climate modeling, attribution and projection. Some of the challenge involves properly representing the small-scale turbulent motions that sustain these clouds in coarse-grid climate models, as well as their mesoscale organization. Fundamental scientific uncertainties also contribute – natural aerosol lifecycles over remote oceans, susceptibility of these cloud regimes to human aerosol perturbations, mixed-phase microphysics, ice nucleating particles, and aerosol sources in sea water and from sea spray. These issues have motivated several recent field campaigns in cloudy subtropical and higher-latitude regions.

This talk will focus on findings from the MAGIC (2012-3) and CSET (2015) campaigns over the NE Pacific and the Southern Ocean Climate Studies (2016-8), comprising several observational campaigns (SOCRATES, CAPRICORN, MICRE and MARCUS) sampling between Tasmania and Antarctica, including airborne, ship and island measurements. Higher natural aerosol concentrations were observed over the Southern Ocean than over subtropical regions both in and above the boundary layer, despite more precipitation. Biologically-induced new particle production not well represented in climate models is at least as important to this finding as the higher wind speeds of the midlatitude storm tracks. In both regions, multiple layers of low-lying cloud weakly coupled to surface-driven turbulence and aerosol sources are common. Over the Southern Ocean, supercooled liquid dominates thinner cloud layers at temperatures above -30 C. Hindcast simulations with climate models nudged toward reanalysis-derived meteorology are advocated as a strategy for using field campaign observations to test and improve climate model parameterizations.

Morning session: Topic II / 195

### Response of shallow convection to aerosol perturbations in the Sulu Sea: The role of shear

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In anticipation of the upcoming Cloud, Aerosol and Monsoon Processes Philippines Experiment (CAMP<sup>2</sup>Ex) we simulate the response of shallow convection to aerosol perturbations with large eddy simulation (LES). Prior work has proposed the existence of a buffering mechanism where microphysical suppression of precipitation is offset by enhancement in precipitation due to cloud deepening, such that the overall response is small. Our LES is set up with warm phase bin microphysics (activation, condensation/evaporation, collision-coalescence/breakup), a representation of the aerosol budget, and prognostic calculation of supersaturation. Simulations are run for 60 h on domains of 50 km ( $D_x = 100 \text{ m} \times 100 \text{ m}$ ;  $D_z = 40 \text{ m}$ ) for no-wind shear, and wind shear conditions using an input sounding from the Seven South East Asian Studies (7-SEAS) experiment and reanalysis data. For the range of aerosol inputs ( $35 - 230 \text{ cm}^{-3}$ ), simulations exhibit differing degrees of buffering. The deepening effect is more apparent for the non-shear case so that domain mean precipitation increases in response to aerosol increases. Deepening is less apparent for the shear case so that domain-mean precipitation decreases with aerosol increases. While aerosol conditions have a moderate influence on domain mean precipitation, distinct effects on cloud field organization are apparent, with higher aerosol loadings exhibiting stronger organization. A deeper analysis of the results will be presented at the meeting.

**Morning session: Topic II / 109**

## **Shallow Convection and Precipitation over the Southern Ocean: Case Studies during the CAPRICORN Field Campaign**

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Persistent biases in the energy budget over the Southern Ocean (SO) within climate simulations and reanalysis products have been linked to the poor representation of the unique clouds over the region, particularly in regions of shallow, post-frontal convection. Satellite observations suggest that this region is fundamentally different than over comparable oceans in the Northern Hemisphere.

In response to these challenges, the CAPRICORN (Clouds, Aerosols, Precipitation, Radiation, and atmospheric Composition Over the southern ocean) field campaign was carried out under the broad banner of SOCRATES to characterize the cloud, aerosol, precipitation and boundary layer properties over the SO. The Australian R/V Investigator undertook a 35-day cruise from March to April in 2016 making observations from Hobart (~43°S) to the polar front (~53°S). The ship was instrumented with a cloud radar, a lidar, a micro rain radar, a 2-channel microwave radiometer and a disdrometer. Regular radiosondes were also launched throughout the campaign.

Two cases are examined in this study with a focus on shallow convective clouds that were commonly observed during the cruise. Shipborne measurements, Himawari-8 products, and high-resolution simulations with a convection-permitting configuration of the Weather Research and Forecasting (WRF) model are integrated to investigate the dynamical and microphysical characteristics of the targeted cloud fields. In the first case (21–23 March), a rapid succession of two fronts were encountered, separating fields of shallow convective warm clouds. Light precipitation (~2 mm) originating from the prefrontal shallow convection (cloud-top height below 1 km) was recorded by the ship. This precipitation is underrepresented in the simulations, which is linked to a deficit of the low-cloud cover. The second case (26–28 March) focuses on a sustained period of open mesoscale cellular convection in a post-frontal environment. The observed cloud field in this case resided primarily below 2.5 km and in the sub-freezing temperature range (0 to -8°C), where mixed-phase cloud tops were suggested by both the shipborne and Himawari-8 observations. Relatively heavy precipitation was observed

to be generated from these clouds. Despite the relatively good representation of some surface meteorology, WRF simulations have difficulties in producing both the low-level cloud field, mixed-phase cloud tops, and precipitation.

Sensitivity experiments with different physical parameterisation schemes and modified microphysical parameters are performed to investigate the impact of boundary layer and microphysical processes on the simulations of the shallow convective clouds. Possible causes of the model deficiencies and possible pathways for model improvements will be discussed.

**Morning session: Topic II / 205**

## **Estimating the shallow convective mass flux from the sub-cloud layer mass budget**

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Differences in the warming response of trade-wind cumuli between climate models and large-eddy simulation (LES) mostly occur near cloud base. While cloud-base cloudiness in climate models is very sensitive to changes in the environmental conditions, the opposite is true for LES. In preparation for the EUREC4A field campaign, we use the sub-cloud layer mass budget to test whether convection acts as a negative feedback on humidity and cloudiness near cloud base (the so-called 'cumulus-valve mechanism'). We estimate the shallow convective mass flux as a residual of the mass budget and quantify the contribution of the different budget terms to the magnitude and variability of the mass flux. The analyses are based on four days of ICON-LEM simulation during NARVAL1 in December 2013, at a grid spacing of 150m on a ~100x200 km<sup>2</sup> domain upstream Barbados.

We define the sub-cloud layer top  $h$  as the level of neutral buoyancy of a surface-lifted parcel plus a fixed overshoot of 15% of the mixed layer depth. The entrainment rate at  $h$  is calculated using the flux-jump relationship. Comparison with the mass flux diagnosed directly from the simulated cloud-core area fraction and vertical velocity shows that the estimated mass flux successfully reproduces both the magnitude and the diurnal and day-to-day variability of the diagnosed mass flux. Excluding temporal fluctuations in  $h$  and omitting periods of substantial precipitation improves the agreement between estimated and diagnosed mass flux. Further refinements can be achieved by accounting for the sub-cloud layer convective available potential energy and the transition layer strength in calculating  $h$ .

We find that day-to-day variations in the mass flux are mostly explained by variations in large-scale subsidence, whereas the entrainment rate is very similar among the different days analysed. The entrainment rate instead exhibits a distinct diurnal cycle, with a minimum of about 1 cm/s around sunset and a maximum of about 1.75 cm/s around sunrise. The applicability of the method to observations will be tested with data from NARVAL2, and implications for cloud-base cloudiness will be discussed.

**Morning session: Topic II / 191**

## **Disappearing Drizzle - evaporation under marine boundary layer clouds**

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Drizzle and light precipitation are very common in marine boundary layer (MBL) clouds - about two thirds of MBL clouds observed at the Eastern North Atlantic (ENA) site in the Azores produce drizzle at cloud base. Evaporation of drizzle not only returns vapour to the sub-cloud layer, but also cools and stabilises it. Thus drizzle evaporation is an important factor in determining the boundary layer state and cloud properties.

Global models have a hard time representing the properties of the MBL well: Systematic biases in cloud water content and radiative effects are common, and most models produce light surface precipitation too frequently. The rate of drizzle evaporation, which simultaneously impacts the water and energy budgets of the MBL, is currently poorly constrained in models. It is highly sensitive to assumptions about how humidity varies horizontally within the model column, or which part of the column the drizzle falls into as this determines the amount of sub-saturation encountered. Fall speed and drop size also impact the rate at which the drizzle evaporates.

The recent development of improved drizzle retrievals from the ARM ground-based instrument observations provides crucial information to constrain model parameterisations. A quantitative measure of drizzle evaporation within the MBL can be used in conjunction with existing cloud retrieval products (e.g. liquid water path, fractional cover) and high (temporal) frequency observation of the boundary layer state (temperature, humidity) to assess and improve the parametrization of drizzle evaporation in models.

We illustrate this approach using stratocumulus cases observed at the ENA site and Single Column Model (SCM) simulations with the ECMWF Integrated Forecast System (IFS). The observations show appreciable evaporation not far from cloud base, rapidly reducing drizzle rates and in many cases fully evaporating the rain before it reaches the surface. In contrast, drizzle evaporation in the model occurs primarily in the lowest few layers above the surface. The observations also show that in broken cloud scenes, drizzle falls into moister-than-average subcloud air. Changes to the SCM that impact the evaporation rate beneath cloud base are tested and evaluated in the SCM environment, leading to a better understanding of the representation of drizzling boundary layer cloud processes in models for weather and climate prediction.

**Morning session: Topic II / 215**

## **Nocturnal low-level stratus clouds over southern West Africa: Insights from the DACCIIWA field campaign**

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During the summer monsoon season in southern West Africa, low-level stratus clouds (LLC) form frequently in the boundary layer during the night. These clouds have a distinct diurnal cycle, as they often persist long into the following day and consequently transition into convective clouds. These LLC cover a large area and affect the surface radiation budget and thus the regional climate. Up to now, investigations of LLC in this region have been performed based on satellite images, synoptic observations and few modelling studies, however, little is known about the processes controlling their evolution, maintenance and dissolution.

In order to close this gap, a comprehensive field campaign within the Dynamics-aerosol-chemistry-cloud-interactions over West Africa (DACCIIWA) project was conducted during 2016 monsoon season at three supersites in Ghana, Benin and Nigeria. The comprehensive and unique data set, which consists of remote sensing and in situ data, enables, for the first time, the investigation of cloud characteristics and dynamic and thermodynamic conditions at high temporal and vertical resolutions in this area. The aim is to study LLC characteristics, the intra-night variability of boundary layer



conditions and physical processes relevant for the diurnal cycle of LLC. Additionally, the relative importance of the different processes is assessed.

We find that during the DACCIWA campaign typically five different phases can be identified: the Stable, Jet, Stratus fractus, Stratus and Convective phase. Mean profiles calculated for the individual phases reveal pronounced differences. The analysis shows that relevant processes include the horizontal advection of cool maritime air from the Gulf of Guinea embedded in the monsoon layer, formation of a nocturnal low-level jet (NLLJ) and shear-related turbulent mixing.

Cooling is a dominant process for LLC formation, leading to a continuous increase of relative humidity, until finally saturation is reached and LLC form with a cloud-base height near the height of NLLJ maximum. About 50 % of the cooling prior to the LLC formation is caused by horizontal cold air advection, roughly 20 % by radiative flux divergence and about 22 % by sensible heat flux divergence in the presence of a NLLJ (Jet phase). After the LLC form (Stratus phase), turbulent mixing supports the cooling below the cloud base, while strong radiative cooling at the cloud top helps to maintain thick stratus. Based on the analysis of data gathered during the DACCIWA field campaign, we developed a conceptual model on LLC formation, maintenance and dissolution over southern West Africa.

**Morning session: Topic II / 104**

## **Dissecting the role of various precipitation micro-physical processes in Arctic clouds using ICECAPS observations**

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Constraining and quantifying the role of ice- and mixed-phase microphysical processes remains a challenge both in terms of process understanding and model parameterizations.

Our NSF-funded Integrated Characterization of Energy, Clouds, Atmospheric state, and Precipitation at Summit, Greenland (ICECAPS) experiment is located at 3200 m altitude on top of the Greenland Ice Sheet and has been operational since 2010. Because of its high and cold location it provides a unique opportunities to study ice- and mixed-phase microphysical processes.

In this presentation I will address the relative importance of riming, aggregation, and ice particle diffusional growth in high-latitude precipitation generation. I will compare observational results with model studies in order to understand the relevance of these processes in precipitation generation and their link to the large-scale environment.

The importance of different processes varies strongly between precipitation events and appears to be largely driven by integral properties of the atmosphere, which in turn are determined more by the large-scale flow than by microphysical details. If appropriate integral constraints can be identified, such constraints can be utilized to validate and narrow down uncertainties in cloud microphysical parameterizations.

**Morning session: Topic II / 129**

## **Cloud processes in air-mass transformations between the Arctic and mid-latitudes**

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Pulses of warm and moist air from lower latitudes provide energy to the Arctic and form its main energy source outside of the summer months. These pulses can cause substantial surface warming and trigger ice melt. Air-mass transport in the opposite direction, away from the Arctic, leads to cold-air outbreaks. The outbreaks are often associated with cold extremes over continents, and extreme surface heat fluxes and occasional polar lows over oceans. Air masses advected across the strong Arctic-to-mid-latitude temperature gradient are rapidly transformed into colder and dryer or warmer and moister air masses by clouds, radiative and turbulent processes, particularly in the boundary layer. Phase changes from liquid to ice within boundary-layer clouds are critical in these air-mass transformations. The presence of liquid water determines the radiative effects of these clouds, whereas the presence of ice is crucial for subsequent cloud decay or dissipation, processes that are poorly represented in weather and climate models. We argue that a better understanding of how air masses are transformed on their way into and out of the Arctic is essential for improved prediction of weather and climate in the Arctic and mid-latitudes. Observational and modelling exercises should take an air-mass-following Lagrangian approach to attain these goals. We demonstrate how Eulerian observations from the SHEBA campaign can be used in a Lagrangian approach to understand the transformation of moist air masses advected towards the site.

Review paper

**Morning session: Topic II / 250**

## **How can we utilize the full potential of novel synergistic radar observations to provide constraints for ice microphysical parametrizations in ICON?**

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Understanding ice microphysical processes is equally challenging for modelers and observationalists because of the vast number of degrees of freedom involved. Even state-of-the-art two-moment schemes as implemented in the new German ICOSahedral Nonhydrostatic (ICON) model are still facing problems to correctly reproduce ice microphysical processes such as depositional growth, aggregation, or riming. Without question, there is an urgent need for comprehensive observational constraints to evaluate and improve ice parametrizations.

For thick ice clouds, three main radar remote sensing methods are commonly used to obtain observational fingerprints of the complex ice microphysical processes: Radar polarimetry, multi-frequency applications, and Doppler spectral analysis. Each of these methods has its specific strengths and weaknesses. For example: Polarimetry is very sensitive to asymmetric ice particles but more spherical aggregated and rimed snow show similar polarimetric fingerprints. The new field of triple-frequency radar observations shows remarkable sensitivity to mean size and density of the ice particles which is ideal to study aggregation. Doppler spectra on the other hand are able to capture the change in terminal velocity of the ice particles. Therefore, particle mixtures and particularly rimed

particles can be distinguished very well with spectral approaches. For the first time, all three approaches could be combined thanks to a measurement campaign at the Jülich Observatory for Cloud Observations – Core Facility (JOYCE-CF) super-site during winter 2015/2016.

In the dataset we identified a frontal case whose temporal and spatial structure is well captured in the ICON-LEM run provided within HD(CP)<sup>2</sup>. The added value of the radar combination will be demonstrated on this case focusing on the well-known dendritic growth zone around -15° C and associated aggregation further down in the cloud. While the triple-frequency observations provide the strongest constraint to aggregation processes in the lower part of the cloud, the combination of Doppler spectra and polarimetry reveals interesting insights in the early development of the ice particles aloft. Initial forward simulations of the ICON output for the entire case reveal that the major source of model-obs differences are related to the aggregation process.

**Poster Session A / 49**

## **Pair Correlations and Canonical Statistics of Deep Convection over the Tropical Atlantic**

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Over the tropical oceans, the large-scale, meridional circulation drives the accumulation of moist and warm air, leading to a relatively narrow, convectively active band that interacts with this heterogeneous environment. Furthermore and possibly due to self-aggregation feedbacks, deep moist convection organizes into multi-scale structures that strongly impact the Earth's hydrological cycle and radiation budget. Therefore, the current study investigates deep moist convection in the tropical Atlantic region with the help large-domain, storm-resolving simulations. Deep convective cells are identified with object-based techniques and analyzed with respect to their structural behavior and spatial arrangement. A method is introduced that allows to estimate pair correlations of deep convective cells even in the heterogeneous tropical belt. Based thereon, it is shown that, on average, the probability is more than twice as high to find pair distances of cells closer than 100 km compared to a random distribution. Additionally, the spatial arrangement of larger or stronger cells deviates much more from randomness than that of smaller or weaker cells which might be related to their stronger dynamical feedbacks. Using methods from statistical physics, it is shown that a simple canonical ensemble of interacting cells can reproduce several configurational characteristics of its more realistic counterpart.

**Poster Session A / 238**

## **Understanding the moisture variance in precipitating shallow cumulus convection**

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Precipitation from shallow cumulus clouds leads to cloud organization, e.g. clusters or mesoscale arcs. The precipitation and the associated organized motions influence the second order moments, especially the variances and covariances of moisture and heat. The present work examines this effects, focusing on the moisture variance for the precipitating shallow cumulus convection.

The study addresses the evolution of the moisture variance, the physical mechanisms behind the variance increase and its link to the dynamics using data from idealized large-eddy simulations for the Rain in Cumulus over the Ocean (RICO) field experiment. Results show that the increase in variance correlates well with the presence of dry downdraft within the subcloud layer and moist updraft in the cloud layer. The quantification of vertical distribution of moisture variance shows the importance of the inversion region in the generation of variance. Furthermore, the conditional averaging demonstrates the role of cloud active (CA) and non active (NA) areas and the contribution of horizontal transport between these regions are also examined. Microphysics acts as an additional sink term in the variance budget analysis.

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Poster Session A / 123

## Lagrangian trajectories in high-resolution simulations of convective systems

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Lagrangian trajectories provide insights into the flow structure and transport of moisture and trace gases in the atmosphere. Applying Lagrangian tools to high-resolution simulations of convective systems enables us to understand the life cycle of these systems in more detail. We are able to study the moisture origin and the convective transport over the lifetime of the convective system and follow the history of the transported air parcels.

For life cycle studies of convective systems in high-resolution simulations, Lagrangian tools should deal not only with the high spatial but also with the high temporal resolution of the model system. Performing such an analysis as a post-processing step hits bottlenecks of the input/output system, as we have to write data frequently to provide an accurate Lagrangian analysis. Applied during the model simulation, the on-line tool can access and aggregate data at every model time step.

We implemented the novel Lagrangian trajectory tool LaMETTA (Lagrangian MESSy Tool for Trajectory Analysis) in the ICON (ICOsahedral Non-hydrostatic model system). Utilising the MESSy (Modular Earth Submodel System) interface, which is implemented in the ICON during the HD(CP)<sup>2</sup> (High Definition Clouds and Precipitation for advancing Climate Prediction) project, the Lagrangian trajectory tool is applied on-line during the simulation. It is designed to work on highly parallelised systems, optimised for moderate inter-process communication and memory consumption. A mechanism to start new trajectories automatically during the simulation in confined areas of interest, depending on criteria favouring the development of convection, is implemented. This improves performance and reduces the volume of data output, as the number of trajectories in the model system is reduced. A possibility to start trajectories in combination with an enhanced feature identification is being worked on. A first application of the Lagrangian trajectory tool with this automatic seed generation based on a simple vertical wind threshold criterion look promising, creating trajectories transported into the simulated convective systems. Further possibilities of the selection criterion will be explored.

We introduce this novel Lagrangian trajectory tool and provide some detail on the challenges resulting from the high-resolution multi-core implementation. Preliminary results of applying the Lagrangian on-line trajectories in high-resolution simulations of convective systems will be shown. Some future applications of extracting characteristics of simulated convective systems from on-line trajectories and the integration with on-line feature tracking will be discussed.

Poster Session A / 45

## Cloud feedbacks in extratropical cyclones: insight from long-term satellite data and high-resolution global simulations

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Extratropical cyclones provide a unique set of challenges and opportunities in understanding variability in cloudiness over the extratropics (poleward of 30°). We can gain insight into the shortwave cloud feedback from examining cyclone variability. Here we contrast global climate models (GCMs) with horizontal resolutions from 7 km up to hundreds of kilometers with Multi-Sensor Advanced Climatology Liquid Water Path (MAC-LWP) microwave observations of cyclone properties from the period 1992-2015. We find that inter-cyclone variability in both observations and models is strongly driven by moisture flux along the cyclone's warm conveyor belt (WCB). Stronger WCB moisture flux enhances liquid water path (LWP) within cyclones. This relationship is replicated in GCMs, although its strength varies substantially across models. This relationship is used to propose two cloud feedbacks acting within extratropical cyclones: a negative feedback driven by Clausius-Clapeyron increasing water vapor path (WVP), which enhances the amount of water vapor available to be fluxed into the cyclone; and a feedback moderated by changes in the life cycle and vorticity of cyclones under warming, which changes the rate at which existing moisture is imported into the cyclone. We show that changes in moisture flux drive can explain the majority of the observed trend in Southern Ocean cyclone LWP over the last two decades. Transient warming simulations show that the majority of the predicted change in cyclone LWP within GCMs can be explained by changes in WCB moisture flux, as opposed to changes in cloud phase. Based on this analysis it is suggested that accurate modelling of midlatitude precipitation processes plays a key role in determining extratropical cloud feedbacks.

**Poster Session A / 36**

## Predictability of a Mediterranean Tropical-like Cyclone in storm-resolving simulations

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Predicting the trajectory and structure of Mediterranean Tropical-like Cyclones (MTLCs) has always been a challenge even within a few hours of verification time, given the inadequacy of Numerical Weather Prediction (NWP) models to resolve the relatively small spatial scale of these systems. In

particular, the event of 7-8 November 2014 was poorly predicted by operational NWP models which failed in reproducing the trajectory of the cyclone.

Using a storm-resolving non-hydrostatic model we show that simulations with a grid spacing of approximately 1 km are able to reproduce the fine-scale structure of this MTLC. Simulations performed with grid spacing larger than 2.5 km fail to represent the features of the cyclone, while additional nested simulations with very high resolution (300 m) reveal the ability of the model to fully capture the internal structure of the cyclone. Thus, there is a noticeable convergence towards the observed trajectory of the cyclone with increasing resolution.

Finally, a Potential Vorticity (PV) analysis highlights the mutual interaction between a PV streamer and a low-level PV maximum induced by convection. Only convection-resolving simulations, with a grid spacing smaller than 5 km, show a low-level maximum of PV which impacts the redistribution of PV also in the higher atmospheric levels.

Poster Session A / 57

## **Influence of subgrid-scale parameterizations on the development of clouds in high resolution simulations**

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Process understanding of shallow cumulus clouds is a task intensively focused in today's research because these clouds have multi-scale effects on the atmospheric flow. Large-eddy models (LEM) are widely used to analyze processes connected to the evolution of these clouds by simulating motions in the atmospheric boundary layer and the entrainment zone explicitly. Because LEMs tend to be very sensitive to the turbulence closure, one of the most pressing but yet challenging tasks is to parameterize the subgrid-scale (SGS) motions adequately.

In the LEM of the Icosahedral Nonhydrostatic model (ICON-LEM), the default turbulence parameterization was based on a diagnostic subgrid viscosity formulation (Smagorinsky model). Simulations based on the prognostic SGS turbulent kinetic energy (TKE) equation (Deardorff model) are known to perform better than the models with Smagorinsky closure because the first explicitly account for advective and diffusive transport terms as well as time-rate-of-change in the SGS-TKE equation. Therefore a prognostic equation for the SGS-TKE was implemented into ICON-LEM to account e.g. for compensating SGS fluxes due to the increased production of SGS-TKE in the entrainment zone. Additionally, the LEM was replenished with a basic statistical subgrid cloud cover scheme to replace the existing all-or-nothing scheme. Even with a relatively fine mesh, the latter tend to underestimate cloud activity by assuming that no subgrid-scale variability of water variables exists. Especially near cloud boundaries, substantial portions of the grid volumes contain saturated air. On the other hand parts inside cumulus clouds can contain unsaturated air due to entrainment processes. A statistical subgrid cloud cover scheme covers these effects and allows partial cloud fractions that are also crucial for the radiative budget of the clouds.

Results of both idealized, as well as realistic case simulations, will be analyzed with respect to the grid spacing to show the impact of the implemented schemes.

Poster Session A / 307

## **Response of extreme precipitating cell structures to atmospheric warming**

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With increasing temperatures it is likely that precipitation extremes increase as well. While, on larger spatial and longer temporal scales, the amplification of rainfall extremes often follows the Clausius-Clapeyron (CC) relation, it has been shown that local short term convective precipitation extremes may well exceed the CC rate of around 6.5 %/K.

Most studies on this topic have focussed exclusively on the intensity aspect while only few have examined how warmer and moister conditions modulate the spatial characteristics of convective precipitation extremes and how these connect to increased intensities – with contradictory results.

Therefore we will analyse these relations using Large Eddy Simulations of the diurnal cycle of an extreme precipitating convective event based on a realistic, strongly forced case on a large domain of 200 by 200 km. Systematically perturbed initial conditions of temperature and specific humidity enable an examination of the response of intensities and spatial characteristics of the precipitation field over a wide range of dew point temperatures.

We find that warmer and moister conditions result in an overall increase of both intensities and spatial extent of individual rain cells. Colder conditions favour the development of many but smaller rain cells. Under warmer conditions we find a reduced number of individual cells but their size significantly grows along with an increase of intensities over a large part of the rain cells. Combined, these factors lead to larger and more intense rain cells with the potential of a high impact on a larger area.

## Poster Session A / 108

### Differences between Observed and Large-Eddy Simulations of Shallow Cumulus Cloud-Base Vertical Velocity

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Continental boundary layer clouds are important to simulations of weather and climate because of their impact on the lower atmospheric energy and moisture budgets; unfortunately, model parameterizations remain challenged when it comes to representing the observed properties of these clouds in part because small-scale turbulence and convection are not properly represented. To perform model evaluation and adjustments, observational constraints are needed on critical parameters such as cloud-base vertical velocity and its relationship to cloud cover. In this study conducted at the ARM Facility Southern Great Plains (SGP) observatory in Oklahoma, USA, a network of Doppler lidar observations are used as a benchmark for first-light ensemble large-eddy simulations (LES) conducted by the LES ARM Symbiotic Simulation and Observation (LASSO) project (<https://www.arm.gov/capabilities/modeling/lasso>). Results indicate that simulations significantly underestimate the frequency of occurrence of downdrafts at cloud base. An investigation of potential factors that may contribute to these differences is described, which involves non-standard model configurations and methods for sampling of the cloud field.

**Poster Session A / 74****Ice formation pathways in Warm Conveyor Belts****Author(s):** Tim Lüttmer<sup>1</sup>**Co-author(s):** Peter Spichtinger<sup>1</sup><sup>1</sup> *Johannes Gutenberg-Universität Mainz***Corresponding Author(s):** tluettm@uni-mainz.de

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 new two-moment microphysics scheme in the atmosphere model ICON that distinguishes between different ice modes of origin including homogenous nucleation, deposition freezing, immersion freezing, homogenous freezing of water droplets and secondary ice production from rime splintering, 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.

Model assumptions, e.g. choice of nucleation parameterisations, affect crucially the time evolution of cirrus clouds in the simulations. The developed ice microphysics scheme provides an ideal framework to investigate these sensitivities. We simulate a WCB case using our newly developed scheme in ICON in convection resolving resolution. We investigate the sensitivity of ice modes due to changes in ice nucleation schemes and parameters. Finally, we address the question of dominant ice formation pathways (in situ vs. liquid origin) in case of WCB.

**Poster Session A / 252****Height of convective anvils - What can we learn from high resolution simulations?****Author(s):** Harald Rybka<sup>1</sup> ; Martin Köhler<sup>1</sup>**Co-author(s):** Ioanna Arka<sup>2</sup> ; Ulrike Burkhardt<sup>2</sup> ; Johan Strandgren<sup>2</sup><sup>1</sup> *DWD (German Weather Service)*<sup>2</sup> *DLR (German Aerospace Center)***Corresponding Author(s):** martin.koehler@dwd.de

Convective systems are very climate relevant due to the strong radiative feedbacks. Cloud top heights in particular have a strong impact on the outgoing long wave radiation. The vertical structure of convective systems is dependent on entrainment and detrainment, processes that pose large problems in low resolution models, where they need to be parameterized.

The high resolution ICON-LEM allows resolving the forcing, dynamics and cloud structure of convective systems. We explore a summer day with strong CAPE development and investigate how high these convective clouds reach. The PDF of an ensemble of ICON-LEM simulated cloud top heights will be compared to an artificial neural network CiPS (Cirrus Properties from SEVIRI).

Finally, an updraft-detrainment analysis is attempted from ICON-LEM snapshots to evaluate detrainment rates and levels in ICON-NWP, in which convection is parameterized. Particular emphasis will be given to the question if a bulk mass-flux scheme can realistically describe detrainment profiles and over-shoots. Their accurate simulation is necessary to reduce biases in upper tropospheric temperatures and tropopause heights.



## Poster Session A / 100

**Bridging the Gap between LES and DNS: An Explicit Subgrid Scale Scheme for LES with Particle-Based Cloud Physics**Fabian Hoffmann<sup>1</sup> ; Graham Feingold<sup>2</sup><sup>1</sup> NOAA/CIRES<sup>2</sup> NOAA

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To fully understand the microphysical composition of clouds, their radiative properties, and their ability to precipitate, lengthscales of multiple orders of magnitude need to be considered. During entrainment, for example, the switch from predominantly inhomogeneous to homogenous mixing (and their distinct effects on cloud microphysics) takes place at the centimeter-scale, but standard large-eddy simulations (LES) with grid spacings on the order of decameters exert erroneous homogeneous mixing over the entire subgrid-scale. On the other hand, ultra-high resolution direct numerical simulation (DNS) captures the physics of small-scale mixing correctly, but does not represent the large-scale dynamics of the cloud responsible for entrainment. The challenge is to represent this range of scales with a single model.

In this talk, we present a novel modeling approach in which the LES subgrid-scale is represented by the 'linear eddy model', an economical, one-dimensional model that resolves turbulent compression, folding, and molecular diffusion in each grid box of the LES explicitly. Furthermore, by transforming water vapor supersaturation into a Lagrangian quantity, this new approach mitigates numerical diffusion of this quantity. We apply this approach to test cases of shallow cumuli and stratocumuli, and discuss first applications for mixed-phase clouds. Generally, clouds susceptible to inhomogeneous mixing show a reduction in the droplet number concentration and stronger droplet growth, in agreement with theory. Stratocumulus entrainment rates tend to be lower in the new approach compared to simulations without it. Finally, spurious cloud edge supersaturations and their attendant spurious impacts on the microphysical structure of clouds can be reduced significantly.

All in all, the simulations presented can be seen as a first step to bridge the gap between DNS and LES, allowing an appropriate representation of small-scale mixing processes, but also the consideration of the large-scale cloud system.

## Poster Session A / 84

**A route towards Monte-Carlo Lagrangian methodology based on a physically-based stochastic equation for a cloud microphysical process**Junghwa Lee<sup>1</sup><sup>1</sup> Leibniz University Hannover

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The effect of aerosol-cloud interaction has been identified as crucial to estimate the radiative properties of clouds, their role in the hydrological cycle, and accordingly their influence on the climate system (e.g., Stevens and Feingold, 2009). Therefore, process-level study of the interaction of clouds and aerosols is a crucial element for our understanding of the global climate. However, the consideration of these processes in climate prediction models is challenging because they involve a wide range of spatial and temporal scales that are usually unresolved, starting from entire, but shallow, cloud systems, individual clouds, their micrometer-sized droplets and the even smaller aerosols. The particle-based Lagrangian methodology has experienced growing popularity for understanding clouds' physical processes. Previously, two Eulerian approaches have been used to investigate cloud microphysics for decades: the first is the bulk microphysics model, and the second is the spectral bin-resolving model. In addition to the traditional Eulerian approaches, the Lagrangian methodology

referred to as “Super-droplets” can directly represent the condensational growth and the collision-coalescence process. (see, Riechelmann et al., 2012). The Lagrangian methodology coupled with Large Eddy Simulation (LES) have improved the state-of-the-art in the field of cloud microphysics with the help of exponential growth in the computational power. The motivation of the model is that it does not need any parameterizations while solving fundamental equations. Despite their growing popularity, however, the traditional Eulerian approaches remain more popular. Until now, it is still too expensive to fully convert the large-scale prediction system to the Lagrangian methodology. Therefore, parameterization for the large-scale model and providing hidden pattern based on explicit calculations have recently been combined aiming towards the goal of improved weather predictions. So, this study presents a route towards Monte-Carlo Lagrangian methodology based on physically-based stochastic equations in the LCM-LES. Here, we implement Monte-Carlo methodology into three processes: first is the advection of the super-droplets, second is the fluctuations in supersaturation fields, and finally terminal fall speeds. The advantage of Monte-Carlo Lagrangian methodology is that it can act for small-scale variability without considerable efforts to explicitly solve small-scale processes. Therefore, the method can help to reduce computational efforts by following formation and growth of natural cloud physics simultaneously.

**Poster Session A / 168**

## **When the plants wilt, the rain comes**

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Understanding important factors determining the spatial distribution of precipitation over land is frustrated by a lack of consensus as to the basic effect of soil moisture on precipitation. Such effects are often blurred by the complexity of the land-atmosphere system or biased by the use of convective parameterizations. Here we take a simpler approach and apply the radiative convective equilibrium (RCE) framework to an idealized land planet that only retains the basic control of soil moisture on precipitation. The goal is to understand whether soil moisture acts to support or to impede the organization of convection.

Results of our convection-permitting simulations show that, initially, shallow circulations driven by differential radiative cooling induce a self-aggregation of the convection into a single band, as has become familiar from simulations over idealized sea-surfaces. With time, however, the drying out of the non-precipitating region induces a reversal of the shallow circulation, drawing the flow at low-levels from the precipitating to the non-precipitating region. This causes the precipitating convection to move over the dry soils, and reverses the polarity of the circulation. The precipitation replenishes these soils with moisture at the expense of the formerly wet soils which dry, until the process repeats itself. On longer timescales, this acts to homogenize the precipitation field. By analyzing the strength of the radiatively driven shallow circulation and the shape of the soil moisture resistance function, we demonstrate that only a significant drying of the soil is able to alter the precipitation distribution. Finally we find evidence in observations that support our results.

**Poster Session A / 297**

## **Investigation of ice cloud microphysics and rain formation using simultaneous C- and Ka-band radar observations**

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It is well recognized that ice clouds have a significant influence on the global radiation budget and climate system. Previous studies indicate that improved assessment of the cloud influence requires a better understanding of their microphysical properties, such as ice water content and hydrometeor size, shape, and hydrometeor type. However, estimates of ice water content (IWC) and ice particle size have been severely limited in both temporal and spatial coverage (because of the lack of observational data), which results in a large uncertainty in numerical weather forecasting. Furthermore, important microphysical processes such as the conversion between different hydrometeor classes and ice particle growth are difficult to observe in-situ as well as from single remote sensing observations. The synergy of radars operating at different wavelengths offer a unique way of providing the necessary insight into ice microphysics at a high vertical resolution. For this study, two radars operating at different wavelengths are used for coordinated measurements. The systems are the dual-polarization C-band weather radar Poldirad ( $\lambda=5.45$  cm) located at DLR, Oberpfaffenhofen and the Mira-36 Ka-band cloud radar ( $\lambda=0.85$  cm) at the University of Munich, respectively. The two radars are separated by a distance of about 23 km and have a large overlapping region. The Ka-band radar is vertically probing the atmosphere continuously as well as running a synchronous RHI scan with the C-band radar. Based on the well-established IWC-Ze relationship, we retrieved the IWC from the reflectivity observations with the Ka-band radar and further their statistical distribution. With the synchronous RHI scan with both radars an algorithm to retrieve IWC is presented. Furthermore, dual-wavelength reflectivity ratio (DWR) measurements are used to determine the size distribution of ice crystals.

**Poster Session A / 275**

## **Organization of convective clouds in observations and ICON-LEM simulations**

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With the objective to better understand the impact of convective organization on climate, this study characterizes the organizational state of convective clouds in observations and evaluates its representation in ICON-LEM simulations. First, signatures of convective clouds (objects) are identified in fields of radar reflectivities and satellite brightness temperatures observed over Germany for the summer seasons of the years 2014 and 2015 using a threshold-based segmentation algorithm. To assess the organizational state and the dominant shape of the objects a series of organization indices are applied and compared: the nearest-neighbor distance-based index I.org, the simple convective aggregation index (SCAI), the convective organization potential (COP) and the 2D shape-based index I.shape. In radar observations the objects are organized in about 92% of the summer seasons, while the according signatures in satellite observations are characterized as organized in only 69% of the time. The difference may be caused by the much larger area of the cirrus anvil shields observed by satellite in comparison to precipitation cores detected by radar. Overall organization shows an increase in the rainfall amounts compared to non-organized objects, which, however, seems to be associated with larger number of objects and sizes and not with the organizational state itself. In the second part of the study outputs of ICON-LEM simulations for four selected days are translated into observation space and evaluated their ability to represent convective organizations. In order to investigate also the impact of the model resolution, outputs of the model runs with grid resolutions of 625 m, 312 m and 156 m are considered. Based on the case studies, the most robust indices I.org and COP testify a good representation of convective organization in ICON-LEM at all grid resolutions. SCAI has been identified as sensitive to model deficiencies like underestimation of heavy precipitation and the overestimation of cold cloud coverage, small-scale clouds and precipitation cores and

thus less suited for model evaluation studies. I.shape identifies significant differences in the simulated shapes of the objects for the different grid resolutions. The coarsest simulations with 625 m spatial resolution generate objects with shapes close to the observed ones, while finer resolutions lead to more pronounced deviations. The presented study (i) suggests the combined use of I.org and COP to characterize the organizational state of convective clouds in observations and model simulations and (ii) encourages the use of I.shape for characterizing and evaluating the shape of simulated convective cloud signatures.

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## Concentrations and Properties of Cloud Condensation Nuclei (CCN) and Ice Nucleating Particles (INP) over the Southern Ocean during the Antarctic Circumnavigation Expedition

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As part of the 2016/17 Antarctic Circumnavigation Expedition (ACE) within the ACE-project “Study of Preindustrial-like Aerosol-Climate Effects” (SPACE), we conducted measurements of cloud condensation nuclei (CCN) and ice nucleating particles (INP) concentrations. The unique ship-based circum-Antarctic data we gathered during the Austral summer makes an important addition to the to-date still sparse aerosol data available for the Southern Ocean. Our data will be useful for improving both atmospheric models and satellite retrievals. A CCN-100 cloud condensation nuclei counter was operated during the cruise at 5 levels of supersaturation (0.15 to 1.0%). Particulate matter smaller than 10 micrometer was collected on fiber and polycarbonate filters for offline analysis of INP concentration (*droplet freezing array* method, Conen et al., 2011) and chemical composition at the Institute for Tropospheric Research (TROPOS). CCN concentrations were in the range between 5 and 1300 #/cm<sup>3</sup>, with high values near the continents including Antarctica. The lowest CCN concentrations were observed during particular intervals of the open ocean sections of the cruise. Preliminary INP concentrations show a range of 0.1 to 100 #/m<sup>3</sup>. The highest values are associated to harbours. A connection between bulk chemistry and CCN number was pointed out by a first correlation analysis, excluding cross-correlation between composition and size. No such correlation was found for INPs, as expected. The highest INP concentrations were also found near continents. This could either mean a domination of sinks over the ocean or strong land-based sources. For further elucidation of possible CCN and INP sources, back-trajectory analysis is applied. We will present results concerning the abundance and properties of CCN and INPs and their respective sources, and thereby provide highly valuable data for constraining and/or evaluating climate models and satellite retrievals.

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Conen, F. et al. (2011). “Atmospheric ice nucleators active  $\geq -12^{\circ}\text{C}$  may be quantified on PM<sub>10</sub> filters”. In: *Atmos. Meas. Tech.* 5, pp. 321–327. DOI: [10.5194/amt-5-321-2012](https://doi.org/10.5194/amt-5-321-2012).

Poster Session A / 189

## Effects of Land Surface Heterogeneity on the Simulated Atmospheric Boundary Layer Structure

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Land heterogeneity is expected to influence the vertical atmospheric boundary layer (ABL) structure including the initiation of ABL secondary circulations and related surface-atmosphere exchange fluxes. Such effects cannot be incorporated explicitly in regional weather and climate models, due to their large spatial grid scales. While model simulations using the tile or mosaic approach capture the aggregation effects related to sub-grid scale surface heterogeneity, they cannot handle their dynamical effects, such as the formation of convectively induced secondary circulations. This leads to inherent uncertainties in modeled surface fluxes, boundary layer evolution, cloud initiation, and precipitation.

In the framework of an idealized model study, we examine the effect of surface heterogeneity on the simulated ABL in terms of stability, height and induced secondary circulations for five different grid spacings ( $\Delta x = 300$  m, 600 m, 1200 m, 2400 m, 4800 m) using the ICON model. The numerical simulations are designed to favor either roll or cell-like structures by appropriately tuned soil moisture and wind velocity. For all grid spacings we embedded an equally sized either stripe or block-shaped patch of land use heterogeneity in an otherwise homogenous land cover and soil type being resolved in the simulations with the smallest grid spacing and only partly or not resolved in the simulations with the coarser grid spacings. The numerical experiments reveal, that the dynamical effects due to the surface heterogeneity increase with coarser resolutions, which hints at an overestimation of the effect of land surface heterogeneity on ABL-profiles in coarse-grid simulations. Especially for the smaller grid spacings a frequency and spatial filtering of the vertical velocity fields is required to detect and visualize the dynamical response of the model to the land surface heterogeneities.

Poster Session A / 290

## Assessing the Goddard Earth Observing System model in non-resolved to convection-permitting regimes.

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We evaluate the Goddard Earth Observing System (GEOS) modeling and assimilation through a cascade of simulations with increasing horizontal resolution. The GEOS model is driven by the finite-volume cubed-sphere (FV3) non-hydrostatic dynamical core, a set of scale-aware physics package and data assimilation capability. The GEOS model is run for 40-days beginning in August 2016 at five uniform global resolutions of 50 km, 25 km, 12 km, 6 km and 3 km with 72 vertical levels up to 0.01mb. The model physics use the Grell-Freitas scale-aware convection scheme to dynamically reduce the role of parameterized deep convection as resolved scale processes in the model take over at higher resolutions. We will study the climatology of these simulations in comparison with reanalysis and observations, with a focus on rainfall, clouds and radiative forcing as well as the temperature, water vapor and horizontal wind in the troposphere. Finally, we will look at the capability of the GEOS to realistically represent the diurnal cycle of precipitation over the land and ocean regions across the scales discussed before.

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## Using a cloud-resolving model to diagnose the effects of different wind shear profiles on deep convective cloud fields

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Wind shear is an important factor in the upscale transport of energy in deep convective cloud fields, contributing to the formation organized features such as squall lines and MCSs. Cloud Resolving Models (CRMs) can be used to diagnose the effects of wind shear on the cloud field, investigating e.g. organization, Q1, Q2, bulk entrainment rate and cloud lifetime as a function of the wind shear. Here, we use two sets of wind shear profiles to drive our experiments. The first is a set of scaled profiles known to produced a squall line like feature, which are used to systematically investigate the effect of wind shear on organization. The second is a representative set of wind profiles derived from a GCM, which represent different shear regimes found in a GCM. We present results showing how the different shear profiles affect the cloud field, with particular attention paid to how these results could be used to modify a GCM's convective parametrization scheme.

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## Use of unmanned aerial systems to measure and understand lower atmospheric structure and its connection to clouds and precipitation

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The continued development of model parameterizations to represent clouds, precipitation and turbulence in weather and climate models requires measurements that can provide information on vertical structure and sub-grid scale variability of key quantities. To support development of globally-applicable parameterizations, such measurements must be provided over a wide variety of conditions and locations. Over the past several years unmanned aircraft and tethered balloons have been deployed to make measurements of thermodynamic structure, winds, turbulent fluxes of heat and momentum, turbulence, aerosol properties, and cloud microphysics. These systems can provide high resolution perspectives on the vertical structure of the atmosphere and its evolution, horizontal variability and co-variability of key quantities such as vertical velocity and humidity, and the atmospheric state over difficult-to-sample regions.

In this presentation, we will provide an overview of unmanned aerial systems recently deployed under projects lead by the University of Colorado and the NOAA Physical Sciences Division. The presentation will focus on scientific questions that these systems can help to address, touching upon topics such as lower atmospheric evolution and structure under different cloud regimes, the turbulent structure of the subcloud environment, the influence of clouds on the vertical distribution of aerosol particles, and the use of these systems in advancing our understanding of ice crystal shape. In addition, we will provide information on recent advancements in instrumentation and planned unmanned aerial deployments as part of the upcoming MOSAiC and EUREC4A/ATOMIC campaigns.

**Poster Session A / 209**

## Interplay between shallow convection and stratiform cloud layers

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Clouds carry one of the largest uncertainty in climate projections. Besides frequently occurring shallow cumulus clouds in the trade wind region, thin clouds of stratiform extent are often accompanying shallow convection and create, in symbiosis, various cloud patterns.

Using geostationary satellite data, the high-resolution measurements of shallow convection gathered at the Barbados Cloud Observatory are categorized to study the macrophysical properties of clouds depending on their mesoscale pattern, in particular the ones of stratiform clouds.

Preliminary analysis shows that about 15 % of the measured stratiform clouds in the trade-wind regime occur in a rather regularly distributed cloud field on the large scale – illustratively named *flowers*. Within such an environment stratiform clouds express a different behaviour than within other environments.

This *flower* pattern is one of few organizational patterns of shallow convection. It has its appearance largely from stratiform cloud cover, which can become very thin, but still long lasting. To gain a better understanding of the lifecycle of these clouds and their environmental conditions, differences between the stratiform clouds in an organized environment to a less organized one are discussed.

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## Aerosol and microphysics of a mesoscale cloud system in the stratocumulus-to-cumulus transition during the CLARIFY field campaign

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A mesoscale cloud system located approximately 200 – 300 km south of Ascension Island underwent transition from stratocumulus to cumulus on 19 August 2017 during the CLOUDS and Aerosol Radiative Impacts and Forcing (CLARIFY) field campaign. Extensive aircraft measurements were made with the UK BAe 146 FAAM research aircraft to investigate the aerosol and cloud microphysics during the transition. The base height of the inversion layer was about 2500 m. The mean aerosol concentrations was about 500 cm<sup>-3</sup> below the cloud base. There is an aerosol layer of up to 250 cm<sup>-3</sup> between 2400 – 4000 m. The aircraft penetrated the clouds at five levels from shallow cumulus below the stratocumulus layer, within the cloud layer to the overshooting convective clouds above the inversion cloud layer. The peaks of the cloud drop size distribution function grew from 12 μm at the lowest level to about 27 μm at the highest level. The concentrations decreased for drops smaller than 13.5 μm, but increased for larger drops from low to high level, indicating the operation of the collision-coalescence of drops. In-cloud runs show that the embedded convective clouds had with strong downdraughts and updraughts between -8 m s<sup>-1</sup> to 5.7 m s<sup>-1</sup>. The drop number concentration and effective radius generally increased with the strength of the updraught. The concentration of drizzle drops and raindrops also increased with the strength of the updraught in the lower and mid-level of the cloud layer.

There were a few cloud-free holes and gaps in the cloud layer, associated with downward motion. The few clouds that existed within the gaps contained a much lower drop concentration. In the cloud pass just above the main Sc cloud layer, the aircraft penetrated some overshooting cumulus, and the concentration of aerosol clearly increases with downdraught stronger than -1 m s<sup>-1</sup>. Those strong downdraughts are associated with the penetrating convection and could be a mechanism for

transporting aerosol particles from the overlying aerosol layer into the vicinity of the clouds. The observed features of aerosol and microphysics indicate that the convective clouds significantly affected the Sc cloud properties during the transition.

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## Measuring the tropical shallow convective mass flux

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In most of the models used for operational weather forecasts and climate studies, shallow cumulus clouds and their convective transport are simulated using a mass flux approach, which predicts the vertical structure of cumulus up- and downdrafts. This makes the shallow convective mass flux a key parameter for model simulations.

For this reason, measurements of the shallow convective mass flux are as important as simulations. In this study, we use measurements to derive the shallow convective mass flux by using a cloud radar and a Doppler lidar instrument from the Barbados Cloud Observatory (BCO). The BCO is located on the east coast of Barbados (13° 09' N, 59° 25' W), where it is exposed to the undisturbed easterly trade winds and shallow cumulus clouds are very common. Vertical profiles of the shallow convective mass flux will be shown and compared with prior studies from *Ghate et al. (2011)* and *Lamer et al. (2015)*. Furthermore, we will present its diurnal variability and the relationship to the diurnal cloud cover.

*Ghate, V. P., M. A. Miller, and L. DiPreto (2011), Vertical velocity structure of marine boundary layer trade wind cumulus clouds, J. Geophys. Res., 116, D16206, doi:10.1029/2010JD015344.*

*Lamer, K., P. Kollias, and L. Nuijens (2015), Observations of the variability of shallow trade wind cumulus cloudiness and mass flux. J. Geophys. Res. Atmos., 120, 6161–6178. doi: 10.1002/2014JD022950.*

Poster Session A / 141

## Cirrus IWC, IWP estimation based on IWC measurements with water Raman lidar: Comparisons with Cloudnet IWC and satellite IWP retrievals

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The German Weather Service's RAMSES lidar at Lindenberg Observatory is the first spectrometric combined inelastic elastic-backscatter lidar that routinely measures the water Raman spectra of clouds. This measurement capability allows for direct determination of cirrus ice water content (IWC), and ice water path (IWP). However, because of the extremely weak Raman backscattering by clouds, such IWC measurements are restricted to nighttime observations and often to the lower cirrus layers. For these reasons, the large data set of RAMSES IWC observations was used to develop an analytic expression to estimate IWC profiles from the cross-polarized backscatter coefficient (BSCs) and atmospheric temperature ( $T$ ). The advantages of the newly discovered BSCs-IWC relationship are a substantial increase in the IWC and, particularly, IWP data sets, and its transferability to more



common depolarization lidars.

In this contribution, first a comparison is presented between IWC retrievals provided by Cloudnet (IWC- cloud radar reflectivity factors ( $Z$ ) - $T$  approach) and the IWC profiles measured with RAMSES at Lindenberg. While the Cloudnet IWCs compare well with the RAMSES observations in terms of vertical distribution and temperature dependence, it is found that the former are systematically smaller (about 60%).

Second, a comparison of RAMSES IWP estimates and IWP retrievals obtained from data of satellite-borne radiometers is presented for several temporally extended and spatially homogeneous ice clouds. The CiPS (Cirrus Properties from SEVIRI) and SPARE-ICE (Synergistic Passive Atmospheric Retrieval Experiment-ICE) algorithms were used to retrieve coinciding IWP from the geostationary MSG and during overpasses of the sun-synchronous NOAA-18 and -19 satellites, respectively. It is found that RAMSES, CiPS, and SPARE-ICE IWPs agree well in most cases which is, in view of the fundamentally different observation techniques and retrieval approaches, quite remarkable. On-going work is dedicated to more complex cloud scenes, results of the comparative studies will be presented at the conference.

Poster Session A / 121

## Clouds in month-long convection-resolving climate simulations over the tropical Atlantic

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Despite their crucial role for the Earth's climate, accurately representing cloud processes in climate models poses a compelling and yet unresolved challenge. As an unfortunate consequence, clouds constitute the leading source for uncertainties in climate projections. In this regard, among all cloud types that exist on Earth, trade-wind cumuli stand out as particularly relevant, especially because of their large radiative effect and their critical importance for the global climate sensitivity. Climate studies on clouds typically rely either on Global Climate Models (GCMs) or Large Eddy Simulations (LES). GCMs operate at coarse horizontal grid resolutions ( $O(100\text{ km})$ ) and use cloud parameterizations, while LES operate at a very high-resolution ( $O(100\text{ m})$ ) but over very small domains, where interactions and feedbacks between clouds and meso-scale circulation cannot be satisfactorily captured. Thanks to recent advances in high performance computing, it becomes possible to fill this gap with high-resolution climate simulations over extended domains, using regional climate models. We follow this state-of-the-art approach and perform convection-resolving climate simulations at a horizontal grid resolution of 2.2 km over a computational domain with 2303x1536x60 grid points covering the tropical Atlantic. To run the computationally demanding simulations, we use a COSMO (Consortium for Small-Scale Modeling) model version that runs entirely on Graphics Processing Units.

In this work, we present evaluation of month-long ERA-Interim driven kilometer-scale convection-resolving simulations during the northern hemisphere winter season. Comparison of simulated cloudiness against satellite images show that, unlike simulations with parameterized convection at 12 km horizontal grid resolution, the convection-resolving simulations capture remarkably well the high spatial and temporal variabilities of low-level tropical clouds. This can at least partly be attributed to a more realistic tropospheric mixing in high-resolution convection-resolving simulations. Validation against satellite and observational data shows that this also implies significant bias reduction in precipitation and radiation. Further, noticeable correlations between weather situation and cloud patterns are at least partly captured, and relate to atmospheric properties such as organised shallow cumuli, pronounced low-level inversions, and low-level wind speeds.

The remarkable and promising results obtained with the month-long simulations give confidence in the ability of the kilometer-scale convection-resolving models to realistically simulate low-level tropical clouds. They can thus potentially serve as a robust basis to plan extended simulations over longer timescales in order to investigate climate change.

## Poster Session A / 217

## FESSTVaL: Field Experiment on sub-mesoscale spatio-temporal variability in Lindenberg

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Numerical weather prediction (NWP) models applied on regional scales use a typical grid spacing of O(1 km). While such a grid spacing allows to start explicitly resolving convection - at least deep convection - several features of the flow remain of subgrid-scale nature, e.g. turbulence, shallow convection, or may be distorted by the coarse grid spacing. Large-eddy simulations (LES) with grid spacing of at least O(100 m) can be used to get more information on smaller-scale, generally under-resolved, phenomena. But such simulations also rely on parameterizations, most notably turbulence and microphysics. Getting information on the atmospheric flow on scales O(500 m) from observations remains challenging as the measurement network lacks the spatial resolution. For instance automatic measurement stations of the German Weather Service (DWD) have a typical horizontal distance of O(25 km). This makes the validation of NWP models and LES difficult.

We present the plan for the field campaign FESSTVaL, which deploys a high-density measurement network that will allow us to observe features of the atmospheric flow occurring on scales between 500 m and 5 km. The measurements will be used to (i) improve our process understanding, (ii) validate aspects of convection-permitting NWP simulations and (iii) compare different measurement strategies and instrument types, including a citizen science approach and newly available satellite observations, in view of designing appropriate measurement networks of the future. Finally, in addition to the measurements, various simulations will be performed in support of the field campaign and for validation purposes.

With respect to the source of submesoscale variability, the measurement campaign focuses on three different topics: boundary layer patterns, cold pools, and wind gusts. The four topics are interconnected via cold pools, which both generate boundary layer patterns and wind gusts. Furthermore, usability of citizen-science-based measurements will be investigated. Finally, FESSTVaL will provide a first opportunity to evaluate quality and representativeness of ESA Aeolus products.

The measurement campaign will take place in Lindenberg (east Germany) for an extended summer season in 2020 in the context of HErZ (Hans Ertel Centre for Weather Research). Lindenberg is chosen given the already existing instruments, the support by DWD available on site as well as the relatively flat topography. Moreover Lindenberg experiences more frequent convective activity than many other flat regions in Germany. One particular feature of the planned field experiment is the use of about 100 ground base stations, spread over a 10 km x 10 km domain.

## Poster Session A / 224

## Evaluation of clouds in realistic LES simulations using remote-sensing forward operators and observations

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A detailed understanding of clouds and their macrophysical properties is essential to reduce the uncertainties of cloud feedbacks and related processes in current general circulation models (GCMs). Therefore, a physical consistent and comprehensive cloud evaluation is of great importance, but still very challenging due to the complexity of involved processes. Clouds are additionally parameterized in GCMs due to their coarse resolutions of O(100 km). Novel realistic Large Eddy Simulations (LES) covering large areas resolve clouds directly and thus avoid crude parameterizations. Forward operators applied on the high-resolution output make direct comparisons with observations at similar resolutions possible, allowing for completely new evaluation techniques and possibilities.

A continuous one-month LES simulation with a horizontal resolution of up to 156 m covering large parts of Western Germany was performed with the ICOSahedral Non-hydrostatic Large Eddy Model (ICON-LEM) within the framework of HD(CP)<sup>2</sup>. Physical consistent forward operators for a cloud radar, a LiDAR, and a microwave radiometer are applied on the LES output. Therefore, a full synthetic Cloudnet supersite is created, providing a comprehensive view on clouds, which can be directly compared with the observations. Additionally, the same Cloudnet algorithms are applied on this synthetic dataset to create the Target Classification, which provides detailed information about the cloud structure and phase. Measurements from the Leipzig Aerosol and Cloud Remote Observations System (LACROS) are used as observational reference.

All forward simulations of the three instruments are analysed in detail and compared with the corresponding LACROS measurements. The simulated cloud radar shows an overestimation of frozen hydrometeors in the upper troposphere, indicated by higher reflectivities than of the observations. Rain events are too rare and the intensity is overestimated by the ICON LES, seen by 10 dBz higher reflectivities during rain showers at the cloud radar simulation. The forward simulated Target Classification shows promising results. The potential and possibilities of the synthetic observations are discussed.

**Poster Session A / 184**

## **Measurements of cloud droplets and precipitation particles during selected weather events of Warsaw with shadowgraph imaging technique**

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The present study investigates capability of the “Oxford Lasers VisiSize D30” instrument, which works based on the shadowgraph imaging technique, in measuring cloud droplets and precipitation particles. To this aim, series of measurements have been performed during rain, snow and fog events of past few months in Warsaw, Poland.

Size distributions of cloud droplets, rain drops and precipitation particles have been obtained using a technique which is called “Particle/Droplet Image Analysis” (PDIA). Aforementioned method involves illuminating the region of interest from behind by using incoherent, expanded and collimated laser light beam and collecting shadow images of droplets as well as particles at up to 30 frames or pairs of frames per second with a high resolution digital camera. The laser and camera are triggered so that a single laser pulse freezes the motion of particles/droplets present within the measurement volume during each frame capture. Particles/droplets detected inside the depth of field are then measured based on their shadow images. Lastly, size distributions are built by analyzing series of images. Following this, final results have been compared to the statistical data captured by an “OTT

Parsivel2” laser disdrometer which was mounted at the measurement site in order to demonstrate the performance of PDIA imaging technique. In addition, the instrument also has capability of capturing and analyzing non-spherical particles/droplets, and then storing series of their shadow images on the memory as well. The tests described here demonstrate the technique and establish the potential for further more quantitative studies of size distributions of cloud and rain droplets as well as other precipitation particles.

Poster Session A / 197

## Warm clouds over the tropical Atlantic - insights on liquid water path from synergistic airborne measurements

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Shallow maritime clouds have been identified as a major uncertainty factor in climate predictions. Advanced observations of key quantities such as the liquid water path (LWP) are a key to better understanding of changing climate. Different satellite LWP records differ by a factor up to two in the tropics. Microwave satellites provide the longest LWP record over ice-free oceans for several decades. However, they suffer from large footprints and superposing signals of clouds and precipitation. Therefore we use spatially highly resolved airborne microwave observations complemented by simultaneous radar and lidar measurements to better understand the LWP of warm clouds over the tropical North Atlantic.

The measurements were taken with the HALO research aircraft which was equipped with several remote sensing instruments, all mounted in nadir orientation. The measurements were collected during two campaigns in the dry (NARVAL-1-South) and wet (NARVAL-2) season. Microwave retrievals of the integrated water vapor (IWV) and LWP were developed using a unique database derived from 1.25 km-resolution ICON simulations. IWV comparisons with dropsondes and water vapor lidar shows good agreement with a relative accuracy better than 5%. Ancillary measurements for the detection of clear sky conditions is important for the LWP retrieval as the microwave-only retrieval shows an error larger than 100% for LWP below 20 g/m<sup>2</sup>. Such sensor synergy is crucial as about 65% of the time clouds with LWP below 20 g/m<sup>2</sup> were observed and the radiative impact of these clouds is high. The WALES lidar system is best suited for clear sky detection for both campaigns, as solar reflectance measurements frequently suffered from sun glint during NARVAL-2. A combination of passive microwave and active cloud radar observations allows to extend the application of LWP retrieval to drizzle and light precipitation. Rain detection shows significant skill (equitable skill score > 0.5) for rain water paths between 10 and 150 g/m<sup>2</sup>.

Our analysis of both campaigns shows, that although clouds were more frequent in the dry season and have higher mean LWP of about 65 g/m<sup>2</sup> compared to 44 g/m<sup>2</sup> in the dry season, clouds with ice precipitation as identified by microwave scattering were more frequent in the wet season. As to be expected the IWV clearly shows that the wet season is more humid, but also reveals that the frequency distribution is strongly affected by the choice of the flight pattern. Therefore, the airborne measurements need to be combined with long-term ground and space-borne measurements to draw statistically sound conclusions.

Poster Session A / 243

## Experiments using climatological as well as predicted aerosols in both, an aerosol-aware convective parameterization, and a double moment microphysics scheme

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The Next Generation Global Prediction System (NGGPS) is currently under development in the US. The high-stake goals of NGGPS require to generate a much-advanced global modeling system with state-of-the-art nonhydrostatic dynamics, physics and data assimilation. Since this modeling system will be used for predictions from storm-scale to seasonal, the selection of the advanced physics parameterizations may be the most challenging task for 2019. One of the physics packages considered as the advanced physics suite - developed at ESRL - includes a unified scale-aware parameterization of subgrid cloudiness feedback to radiation (coupled PBL, microphysics, radiation, shallow convection), a scale- and aerosol-aware convective parameterization, and an aerosol aware microphysics scheme. While the microphysics scheme is currently used in the storm scale RAPid refresh (RAP) and High-Resolution Rapid Refresh (HRRR) operational weather prediction models, the aerosol awareness in the convective parameterization was not yet evaluated. In this presentation we will investigate sensitivities to aerosol concentrations for both, resolved and non-resolved precipitation physics. Aerosol concentrations will be derived from climatologies as well as observed emissions for hindcasts (biomass burning, sea-salt, dust, and anthropogenic emissions).

**Poster Session A / 95**

## How likely are cold pools to trigger new convection?

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Convection presents one of the major uncertainties in current weather and climate models. In particular, spatial distribution and diurnal cycle of convection in current convection parametrizations deviate significantly from observations. One important feedback that couples convection to boundary layer dynamics and the surface and is missing in current parametrizations consists of cold pools and gust fronts that form from convective precipitation and downdraughts. These effects can trigger new convection in adjoining areas, which tends to increase convective organization and prolong convective activity. Our aim is to capture the increased probability of triggering due to cold pools and use this information to improve the spatio-temporal structure of convection triggering in the Plant-Craig stochastic convection parametrisation for weather and climate models.

We identify and track individual cold pools and convective cells in high-resolution ICON model simulations over Germany, which allows us to determine the intensity and life-cycle of individual cold pools and associated convection. In an environment with weak large-scale forcing, we find that the majority of convective precipitation is associated with cold pools. The passage of cold pool gust fronts correlates strongly with precipitation at a time delay of 30 min, confirming that the gust fronts play an important role in new triggering. We are planning to extend the analysis to cases with stronger large-scale forcing and background winds.

## Poster Session A / 176

## What are km-scale models missing when triggering convection by cold pools?

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While current weather prediction models are able to explicitly model convection, they still struggle with adequately representing the initiation of convection. One such process is secondary convection initiation driven by cold pools and their gust fronts: precipitating downdrafts generate density currents lead by gust fronts which can provoke the triggering of new convective cells nearby via mechanical and thermodynamic lifting. Misrepresenting such secondary triggering mechanisms can potentially cause a lack of convection organization and skew the diurnal cycle of precipitation. Both a shortage of organization and a deficit in late afternoon precipitation have been observed in current km-scale models. Consequently, a better understanding of these effects and their representation in km-scale models is crucial to enable advancements in forecasting convective precipitation. We address this challenge by identifying cold pools and initiated convective cells in high-resolution ICON model simulations over Germany with model grid sizes from 156m to 625m. We compare cold pool characteristics and probabilities of convection initiation between different model resolutions. We confirm that cold pools are indeed related to missing late afternoon convection. We investigate how cold-pool-driven convection initiation is misrepresented in km-scale models. First results show that vertical velocity amplitudes in cold pool gust fronts, which strongly influence the probability of convection initiation, are significantly lower in coarser resolution runs. This leads to a lower probability of triggering new convection at gust fronts at coarser resolution. This improved understanding of cold-pool-driven convection initiation and the corresponding deficits in km-scale models will be used to develop a perturbation scheme for use in kilometer-scale models that will increase convective initiation, leading to better precipitation forecasts.

## Poster Session A / 260

## A two-energies turbulence scheme

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A new turbulence scheme with prognostic equations for two turbulence energies is presented. The two-energies turbulence scheme is inspired by the ideas of Zilitinkevich et al. (2013), but is valid for the whole stability range and includes the influence of moisture. The two-energies scheme is similar to a standard TKE scheme, but its stability parameter is linked to the two prognostic turbulence energies: TKE and an additional prognostic energy, which represents the effects of the temperature and moisture variances in compact form. The energy-dependent stability parameter inherits non-local and prognostic properties from the two turbulence energies and thus allows the modeling of both turbulence and clouds in the planetary boundary layer. The turbulent fluxes in the scheme are however still down-gradient and proportional to the local gradients of the diffused variables. In order to treat boundary layer clouds and turbulent mixing consistently the Assumed Probability Density Function (APDF) method is used for computation of the buoyancy flux and the cloud fraction. The higher order moments, which are required to determine the shape of the trivariate probability density function, are diagnosed from the turbulent fluxes and the two prognostic energies. We implemented the turbulent core of the Cloud Layers Unified By Binormals (CLUBB) model and the two-energies scheme into the ICOSahedral Non-hydrostatic (ICON) Single Column Model (SCM). We will present results of the coupled ICON-CLUBB SCM and the ICON-Two-Energies SCM for selected idealized cases.

**Afternoon session: Topic II / 226**

## **Novel Observations of Convective Updraft Strengths and Cold Pool Variability during the C3LOUD-Ex Field Project**

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Although numerous advancements have been made in recent years regarding our understanding of and ability to simulate convective storms, several common shortfalls persist. Two such shortfalls include the following: (1) Observations from dual-Doppler radar measurements suggest that the magnitudes of simulated convective storm vertical motions may be overestimated; and (2) High spatiotemporal resolution observations of cold pool characteristics are largely lacking. Motivated by these two shortfalls, the CSU Convective Clouds Outflows and UpDrafts Experiment (C3LOUD-Ex) field project was conducted in July 2016 and May-June 2017 in northeastern Colorado and southeastern Wyoming. The primary goals of C3LOUD-Ex were to obtain in-situ observations of convective updraft magnitudes, accomplished using balloon-borne radiosondes and dual-Doppler radar measurements; and to collect high-resolution observations of cold pool characteristics, accomplished using a combination of several portable surface weather stations, radiosondes, a fleet of small unmanned aircraft systems (sUAS), and radar observations. In this presentation, an overview of the updraft and cold pool observations gathered during a few case studies from C3LOUD-Ex will be presented, including such results as (a) in-situ vertical velocity measurements of up to 40-50 m/s within supercell storms; (b) comparison between radiosonde GPS-obtained vertical velocity measurements and dual-Doppler-derived measurements of vertical velocity in midlatitude convection; and (c) variability in cold pool temperature, moisture, and wind properties at spatial scales from 100 m to 1 km, particularly from the fleet of sUAS, highlighting the need for fine resolutions in simulations of cold pools. Implications of the measurements obtained during C3LOUD-Ex for simulations of convective storms will also be discussed.

**Afternoon session: Topic II / 165**

## **The Atmospheric Radiation Measurement (ARM) Facility: Recent Activities and Plans Supporting the Study of Clouds and Precipitation**

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The Atmospheric Radiation Measurement (ARM) facility ([www.arm.gov](http://www.arm.gov)) is operated under the U.S. Department of Energy for the purpose of providing measurements of clouds, aerosols and their interaction with the Earth's energy budget to support the international atmospheric research community. ARM operates a network of three fixed-location atmospheric observatories and three deployable mobile observatories located in diverse meteorological regimes. Recent and upcoming deployments of the mobile facilities include campaigns in the Southern Ocean, the equatorial east Atlantic, Argentina, and two upcoming deployments to the arctic. In conjunction with these deployments and the fixed-location sites, there are a number of recent and on-going activities to enhance measurements and associated data products related to clouds and precipitation. These activities include substantial effort related to the ARM radar network, the implementation of new measurements of clouds and precipitation, the development of associated data products, and the development of a framework for producing high-resolution model simulations to help link ARM observations to large-scale models.

**Afternoon session: Topic II / 312**

## **Cloud observations in 2030**

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The last decades have seen a strong increase in our capabilities to observe cloud and precipitation characteristics and their environmental conditions from the ground, aircraft and space. Technological development both, in in-situ and remote sensing, enables us to probe clouds with a wide repertoire of methods (e.g. multispectral, polarization, holographic, electronic scanning) with always finer detail especially in respect to resolution. Most notable, the synergy of different techniques has fostered improved process understanding, which, however, is still limited as the complex, dynamical development of clouds prevents us from assessing all parameters of interest simultaneously.

In 2030 the latest generation of geostationary satellites will be in its prime time with Meteosat Third Generation (MTG) to be launched in 2021. The drastic improvement in terms of spatial, temporal and spectral resolution compared to the beginning of the satellite era will provide unique opportunities to study the cloud life cycle in the tropics and mid-latitudes. Over the poles, where climate is changing with rapid force, novel insights are expected to come from new instrumentation such as the Ice Cloud Imager (ICI) to be launched in 2023 as part of the MetOp Second Generation. With sub-millimeter wavelengths ICI will close the gap between the microwave and infrared range. Vertical profiling by lidar and radar, demonstrated with enormous impact by the CloudSat / Calipso mission, will be continued by EarthCare with its improved resolution and Doppler capabilities. However, the long-term continuity of active sounding is unsecure and more flexible approaches via miniaturized CubeSats might enhance the global observation system.

Operational ground-based remote sensing using cloud radar, lidar, microwave radiometer etc. has been pioneered by the Atmospheric Radiation Measurement (ARM) program more than 25 years ago and is now on its way into operational services. As the number of atmospheric profiling sites is continuously increasing – from less than a handful in 2000 to nowadays 30 alone in Europe - we expect synoptic stations being widely extended with remote sensing devices in 2030. While some of their measurements are straightforward to use in operational data assimilation to basically constrain cloud environment, e.g. Doppler winds, moisture profiles, microwave radiances, more complex information coming from multi-frequency Doppler radar spectra or multi-wavelength lidar needs to go hand in hand with model development.

With improved satellite and ground-based capabilities still void areas exists for which novel approaches involving in-situ sensor constellations using mobile devices such as unmanned aerial vehicles or phased array scanning radars will play a major role. Ultimately, measurement simulators will become established tools to merge observations and models for exploiting the full information content for applications ranging from process studies via weather prediction to the assessment of climate models using long-term satellite radiance measurements.

**Afternoon session: Topic III / 319**

## **Looking ahead: Opportunities and quandaries facing large eddy-permitting superparameterization and machine learning emulation of cloud physics**

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In the last decade, the 1-4 km horizontal resolution regime was a global modelling frontier that cloud superparameterization (SP) helped explore ahead of schedule. Now, as global cloud resolving models (GCRMs) handle these scales of deep convection more elegantly, it is a good time to reflect



on the next decade's frontier needs. My view is that SP algorithms will remain critical for exploring sub-kilometer scale processes important to global climate, such as low-cloud forming boundary layer turbulence and its mixing with the free troposphere. I will show a first step in this direction ("ultraparameterization"; UP) produces ironically familiar cloud feedbacks to surface warming but interestingly distinct aerosol-cloud indirect effects, suggesting lingering grey zone global sensitivities are yet to be discovered. Looking ahead, I will examine the technical potential for even richer forms of turbulence-permitting SP approaching LES best practices, at computational parity with GCRMs. Finally, I will discuss machine-learning emulation of cloud-resolving simulations, focusing on the unsolved technical issues and interesting philosophical tensions being raised by this disruptive but promising approach.

**Afternoon session: Topic III / 61**

## **Sugar, Flower, Fish or Gravel - Cloud classification from humans to machines**

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Satellite images of shallow clouds show a dazzling variety of organization patterns. These patterns are not only pretty to look at but they can also crucially impact the role that shallow clouds play in a changing climate. Naturally, we would really like to understand these complex structures better. The first problem, however, is that developing objective algorithms to detect cloud patterns turns out to be incredibly complicated.

Here, I will tell the story of a collaborative effort that started in 2017 in Bern where 12 cloud experts came together and manually categorized 1000 cloud scenes according to four patterns: sugar, flower, fish and gravel. This initial effort was the seed for a much larger project that took place in the Fall of 2018. Both, the MPI-M and the LMD organized a cloud classification day in which around 70 participants classified 10,000 images, 3 times each on average. That's 30,000 classifications in total!

This rich dataset, which will be publicly available, provides a new way to explore the meteorology behind these cloud patterns. Further, it serves as ideal training data for modern deep learning algorithms, which allow us to go beyond the human classifications. As a teaser, I will show global patterns of shallow cloud organization and how this data can be used for process-based model evaluation.

**Afternoon session: Topic III / 139**

## **Building a cloud in the Southeast Atlantic: Understanding low-cloud controls based on satellite observations with machine learning**

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Understanding the processes that determine low-cloud properties and aerosol-cloud interactions (ACI) is crucial for the estimation of their radiative effects. However, the covariation of meteorology and aerosols complicates the determination of cloud-relevant influences and the quantification of the aerosol-cloud relation.

This study identifies and analyzes sensitivities of cloud fraction and cloud droplet effective radius to their meteorological and aerosol environment in the atmospherically stable Southeast Atlantic during the biomass-burning season based on an 8-day-averaged dataset. The effect of geophysical parameters on clouds is investigated based on the machine learning technique, gradient boosting regression trees (GBRTs), using a combination of satellite and reanalysis data as well as trajectory modeling of air-mass origins. A comprehensive, multivariate analysis of important drivers of cloud occurrence and properties is performed and evaluated.

The statistical model reveals marked subregional differences of relevant drivers and processes determining low clouds in the Southeast Atlantic. Cloud fraction is sensitive to changes of lower tropospheric stability in the oceanic, southwestern subregion, while in the northeastern subregion it is

governed mostly by surface winds. In the pristine, oceanic subregion large-scale dynamics and aerosols seem to be more important for changes of cloud droplet effective radius than in the polluted, near-shore subregion, where free tropospheric temperature is more relevant. This study suggests the necessity to consider distinct ACI regimes in cloud studies in the Southeast Atlantic.

**Afternoon session: Topic III / 83**

## Improving the numerical robustness of physics parameterizations in global atmosphere models

Hui Wan<sup>1</sup>; Carol S. Woodward<sup>2</sup>; Michael A. Brunke<sup>3</sup>; David J. Gardner<sup>2</sup>; Vincent E. Larson<sup>4</sup>; Huan Lei<sup>1</sup>; Jing Li<sup>1</sup>; Philip J. Rasch<sup>1</sup>; Balwinder Singh<sup>1</sup>; Jeremy A. Sousa<sup>3</sup>; Panos Stinis<sup>1</sup>; Christopher J. Vogl<sup>2</sup>; Xubin Zeng<sup>3</sup>; Shixuan Zhang<sup>1</sup>

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Changes in atmospheric state from physics parameterizations are known to be noisy in time compared to those from the dynamical core, even when the parameterizations are formulated with deterministic equations instead of as stochastic processes. Is this the expected behavior or a numerical artifact? This presentation will introduce our efforts to tackle the noise in two complementary ways:

Motivated by the time-step sensitivities seen in clouds and precipitation simulated by the Energy Exascale Earth System Model (E3SM) and its predecessors, we use simplified but relevant model configurations to demonstrate that noise in the numerical solution can be caused by suboptimal choices in the time integration methods used by physics parameterizations and the coupling between processes. The use of time-step convergence as an accuracy metric can help identify numerical issues as well as vulnerabilities in the model formulation.

Since atmospheric processes with smaller spatial scales are often associated with shorter time scales, it is conceivable that some of the noisiness in the simulations can have a physical basis. For this type of noise, shorter step sizes and advanced time stepping methods can help, but the associated computational costs can be very high. Results from our initial exploration suggest that stochastic modeling can provide a computationally efficient way to improve solution accuracy.

The goal of our efforts is to increase the numerical robustness of the atmospheric simulations and to ensure that the numerical representation of the physical system is not contaminated by artifacts. Our work focuses on E3SM, but similar modeling challenges are expected to exist in other models, too.

**Afternoon session: Topic III / 251**

## **Comparison of Alternative Dynamical Frameworks for Global Cloud-Resolving Models**

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Various approaches are being explored in the rapidly evolving world of dynamical cores for global cloud-resolving models. Issues include alternative equation sets (fully compressible versus sound-proof), alternative choices of prognostic variables (momentum versus vorticity), alternative methods to discretize the sphere itself (icosahedral versus cubic), and alternative vertical staggers (Lorenz versus Charney-Phillips). In this talk we will show comparisons of cloud-resolving simulations with different dynamical cores but identical physics for both idealized (e.g., bubble) and realistic (e.g., TWP-ICE) cases.

We are comparing the merits of several prognostic variables to represent the wind field. These include:

- the momentum vector,
  - the vertical component of the vorticity and the horizontal divergence as in the Z-grid model of Randall (1994),
  - the horizontal vorticity vector as in the “vector vorticity model” (VVM) of Jung and Arakawa (2008), and finally
  - the curl of the horizontal vorticity vector combined with the vertical component of the vorticity.
- The momentum equation is being tested with the fully compressible system of equations, and also the anelastic system and the “Unified System” of Arakawa and Konor (2009). The other three choices are tested only with the anelastic and Unified systems.

All of the dynamical cores currently use the Lorenz grid, although we plan to test the Charney-Phillips grid in the future.

All of the dynamical cores have been coupled with the physical parameterizations of the System for Atmospheric Modeling (SAM; Khairoutdinov and Randall, 2003). We are also comparing our results with comparable simulations using SAM.

The cores are being tested with Cartesian grids on a plane, hexagonal grids on a plane, and geodesic grids. Test cases include dry bubbles, radiative-convective equilibrium, cases based on field data, e.g., TWP-ICE (Fridlind et al., 2012), and idealized baroclinic waves on the sphere.

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**Scientific wrap-up of the day**

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## Clouds, Circulation and Climate Sensitivity: Advances and Challenges (Conference Keynote)

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The coupling among clouds, circulation and climate sensitivity has been recognized as one of the grand science challenges of the climate research community. Four years ago, this grand challenge has been articulated around four main questions, related to the role of cloud feedbacks and convective organization in climate, and to the factors that control the tropical rain belts and the extra-tropical storm tracks. Since then, these questions have inspired creative research on the individual level, and also spurred many initiatives and coordinated activities across the research community. This talk will present some recent advances that have arisen from these activities and help understand of how cloud-circulation coupling affects the climate system. It will show in particular how we have come to realize that the answers to the four questions are intertwined. These advances help define new questions and activities, and set the stage for the next phase of the grand challenge and beyond.

**Morning session: Topic III / 318**

## Cloud-resolving simulations at ECMWF

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I will present results from global simulations with the Integrated Forecast System with up to 1.25 km resolution. This includes a preliminary scientific evaluation of model fidelity but also high performance computing benchmarks.

I will also discuss ways how we may be able to reduce computational cost for these simulations in the future. This will include a discussion of numerical precision and tools from deep learning but also a general discussion about challenges for the use of future high performance computing hardware.

**Morning session: Topic III / 158**

## Comparing LES Approaches for Simulating Convection over the ARM Southern Great Plains Facility in Oklahoma, USA

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Simulating atmospheric convection at high resolution is expensive, requiring compromises that vary depending on the clouds being simulated. One approach is large-eddy simulation (LES) with doubly periodic lateral boundary conditions. This “traditional” approach works well for small-scale clouds but applying it to large clouds becomes costly. Technical difficulties also arise from inadequate representation of mesoscale gradients via the uniform large-scale forcing used with the periodic boundaries.

The LES Atmospheric Radiation Measurement (ARM) Symbiotic Simulation and Observation (LASSO) project routinely simulates continental shallow convection using the traditional LES approach at ARM’s Southern Great Plains (SGP) facility in Oklahoma, USA. To date, the LASSO library includes 47 case dates spanning three shallow convection seasons, with ensembles of data bundles containing model inputs and outputs, related observations, and skill scores and diagnostics indicating model behavior.

An important lesson emphasized via this effort is uncertainty imposed by the large-scale forcing. Additionally, as the library of available simulations grows, it is becoming easier to identify consistent differences between forcing data sets and model biases. For example, simulated cloud-base height is typically higher and low-level cloud fraction lower than observed.

Additional simulations for the 30 August 2016 LASSO case during the HI-SCALE field campaign have been done using a nested LES approach. Comparison of the nested versus periodic boundary methodologies demonstrates how spatiotemporal variability of the boundary information combined with an interactive soil model for the lower boundary substantively changes the spatial characteristics of shallow convection and better captures cloud variability across the region encompassing the LASSO forcing data sets.

While the nested LES approach used for the HI-SCALE case is beneficial for scales on the order of 100 km, it is too small to simulate large convective systems lasting many hours and propagating over large distances. In comparison, a much larger nested LES configuration has been used to simulate a mesoscale convective system during the MC3E campaign. Capturing 18 h of this MCS’s lifecycle requires a domain roughly the width of Oklahoma, and even then, only captures a portion of the storm. This requires substantial computing resources such that few of these simulations can be done. As an alternative, preliminary results will be shown using a simulation domain that moves with the band of convection over the MCS lifecycle. This approach captures many of the convective signatures within the LES domain while reducing the simulation cost by roughly an order of magnitude.

**Morning session: Topic III / 76**

## **HIGH-resolution simulation to improve and TUNE boundary-layer cloud parameterizations, the HIGH-TUNE project**

Fleur COUVREUX<sup>1</sup> ; Frédéric Hourdin<sup>2</sup> ; Romain Roehrig<sup>3</sup> ; Daniel Williamson<sup>4</sup> ; Victoria Volodina<sup>5</sup>

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HIGH-resolution simulation to improve and TUNE boundary-layer cloud parameterizations, the HIGH-TUNE project

F. Couvreux, F Hourdin, R Roehrig, D Williamson, V Volodina and the HIGH-TUNE team

Boundary-layer cloud are key elements of the climate system, however their representation in models are still responsible for important biases in global models. Those clouds are most of the time smaller than a grid cell of global weather forecast and climate models and must be ‘parameterized’ through a set of approximate equations that aims at representing the collective behaviour of an

ensemble of clouds and their impact on the large-scale model variables. Here, we propose a new strategy for process oriented tuning of climate models. This new methodology aims at objectively determining the values of free parameters of the parameterizations of turbulence, convection and clouds, based on comparisons of single-column simulations using parameterized physics with explicit 3D high-resolution Large-Eddy simulations of the same boundary-layer cloud scenes. It consists of applying the statistical tools of the 'history matching' approach developed by Williamson et al (2013) to the context of boundary-layer cloud processes. It allows the exploration of the possible range for the free parameters and rules out impossible values of the parameters based on metrics derived from dynamic and thermodynamic fields. This tool takes into account the uncertainty associated to (i) the reference herein the LES, (ii) the structural error of the model and (iii) the error of the statistical tools. This will be demonstrated on a series of 1D cases covering dry boundary layer and shallow cumulus.

**Morning session: Topic III / 94**

## **Boundary layer cloud life cycle in ICON-LEM and ground-based observations**

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Boundary layer clouds are important for climate because they reflect incoming shortwave solar radiation and contribute to the water cycle with precipitation/evaporation processes. Predicting the response of boundary layer clouds to climate change is associated to large uncertainties, due to their parameterization in climate models. Climate models describe the planetary boundary layer (PBL) by applying so-called PBL-schemes that represent turbulent fluxes and condensation. Since the choice of one PBL scheme can dramatically affect the model output, it is essential to evaluate PBL schemes with observations. PBL parametrizations are developed based on LES models, that are used as virtual labs. LES are evaluated and developed with the help of observations.

The high-resolution (150 - 300 m) Icosahedral non-hydrostatic model (ICON) is developed by the Max Planck Institute for Meteorology (MPI-M) and the German Weather Service (DWD). In this work, we exploit ground-based observations as well as radiosoundings from the JOYCE-CF super-site in Germany to evaluate the PBL representation by ICON-LEM based on two PBL case studies one representing a convective PBL and the other a cloud topped PBL with drizzle. The goal is to understand if the mechanisms for cloud formation are properly described in the model and in which conditions differences and biases are observed.

We first evaluate the description of the dynamics and the thermodynamics during the day. Then, we examine in detail cloud properties investigating correlations with biases observed in dynamic and thermodynamic properties. In addition, we evaluate cloud microphysical properties and the process of drizzle formation in the measurement space by deriving radar Doppler moments with the forward operator PAMTRA: we apply a criterion for drizzle detection to model output as well as observations and we develop an analysis of clouds in a multivariable space including liquid water path, center of gravity and radar Doppler moments.

Preliminary results show that the diurnal evolution of the variance of vertical velocity in the model is too high compared to the observations, and wind shear is underestimated except in the late afternoon.

Despite thermodynamic description of cumulus cloud formation due to surface heating is in very good agreement with observations, clouds are not always forming when they are expected from the thermodynamics. The reasons for such discrepancies are investigated and discussed in detail.

We show that ICON-LEM can be valuable for improving PBL schemes as well as for indicating possible improvements in warm cloud microphysical parametrizations.

**Morning session: Topic III / 71**

## Model development activities at DWD to improve cloud and precipitation forecasts on global and regional scales

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The ICOSahedral Nonhydrostatic (ICON) modelling system, which also provides the basis for most of the modelling activities in HD(CP)<sup>2</sup>, has been used for operational numerical weather prediction (NWP) at DWD since January 2015. Its introduction came along with a substantial improvement of forecast quality in many aspects. Since then, systematic further development of the physics parameterization schemes, the coupling processes among the individual schemes, and the data assimilation system has been conducted. Current activities focus on extending the application range of ICON to convection-permitting forecasts in order to replace the COSMO model by the end of 2020, and on developing a rapid-update cycle data assimilation system to further improve the forecasts of convection and related high-impact weather at very short forecast lead times of 1 to 12 hours.

The presentation will focus on recent development activities to improve cloud and precipitation forecasts in the global NWP system. On the data assimilation side, these involve the assimilation of humidity-sensitive satellite radiances and high-resolution radiosonde data, as well as improvements in the usage of surface observations. On the model physics side, several changes in the convection parameterization have been made in order to reduce the overestimation of widespread light precipitation ("drizzle bias"), including a simple coupling with aerosols to better describe the differences in precipitation efficiency between warm and mixed-phase clouds, and modifications of the triggering mechanism and the related test parcel ascent. Moreover, several issues in the coupling among the parameterization schemes have been fixed, a particularly intriguing example being a problem in the convection-microphysics coupling that led to spurious cloud ice seeding of slightly supercooled stratus clouds if shallow convection was triggered near the top of the stratus deck. Substantial progress has also been made in the field of cloud-radiation interaction, for instance by improving the coupling processes between the cloud cover and convection schemes.

Afterwards, an overview of ongoing and upcoming work in the field of convection-permitting regional forecasting will be given, including aspects of testing strategy and hierarchy as well as technical challenges of handling the huge data amounts coming along with the assimilation of high-resolution remote-sensing data.

**Morning session: Topic III / 179**

## Large-Eddy-Simulations with the ICON-LEM around supersites – bridging the gap between GCMs and point measurements

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The parameterizations of clouds and cloud physics have been a major contribution to the uncertainty of atmospheric models at all scales for a long time. Due to their four dimensional variability and their wide range of sizes, the important processes are both – difficult to measure and model. These difficulties create the need for a synthesis of measurements and simulations in order to enhance our understanding and by this our capabilities to parameterize. During the last decade more and more longterm observational supersites with a variety of ground-based remote sensing instruments have been established, which provide a rather comprehensive picture of clouds and their properties, but

are still limited in dimensions. On the other side the increasing computer resources start to allow us to simulate longer timeseries at high - but of course still limited - resolutions. Especially the development of the ICON-LEM during the HD(CP)<sup>2</sup> project was a large step towards more realistic simulations by enabling open boundaries and topography. Bringing these two tools together - advanced measurement strategies and high-resolution modeling - allows us to finally bridge the gap between point measurements and coarser models with the need for parameterizations. Based on this synthesis, we can use the simulations as a virtual lab for the development of parameterizations, but also to provide a four dimensional context to the point measurements. Using the example of nine days during spring 2013 we analyzed different model setups - including the realistic and an idealized version of the ICON-LEM - in comparison to observations from the supersite JOYCE (Jülich, Germany). We will discuss the questions how and if we can compare Large-Eddy-Simulations to point measurements, how the simulations can help interpreting the measurements and how much information we are losing or gaining by searching for a compromise between domain size and resolution. As a result, we will also present a model testbed setup, which is flexible enough for longterm simulations and can cope with a variety of synoptic situations.

**Morning session: Topic III / 308**

## **What can we learn from cloudy convection in a box? Laboratory meets LES with cloud microphysics**

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Inspired by early convection-tank experiments (e.g., Deardorff and Willis) and diffusion-chamber experiments, we have developed a cloud chamber that operates on the principle of isobaric mixing within turbulent Rayleigh-Bénard convection. The “Pi cloud chamber” has a height of 1 m and diameter of 2 m. An attractive aspect of this approach is the ability to make direct comparison to large eddy simulation with detailed cloud microphysics, with well characterized boundary conditions, and statistical stationarity of both turbulence and cloud properties. Highlights of what we have learned are: cloud microphysical and optical properties are representative of those observed in stratocumulus; aerosol number concentration plays a critical role in cloud droplet size dispersion, i.e., dispersion indirect effect; aerosol-cloud interactions can lead to a condition conducive to accelerated cloud collapse; realistic and persistent mixed-phase cloud conditions can be sustained; LES is able to capture the essential features of the turbulent convection and warm-phase cloud microphysical conditions.

It is worth considering what more could be learned with a larger-scale cloudy-convection chamber. Turbulence Reynolds numbers and Lagrangian-correlation times would be scaled up, therefore allowing more enhanced role of fluctuations in the condensation-growth process. Larger vertical extent (of order 10 m) would approach typical collision mean free paths, thereby allowing for direct observation of the transition from condensation- to coalescence-growth. In combination with cloudy LES, this would be an opportunity for microphysical model validation, and for synergistic learning from model-measurement comparison under controlled experimental conditions.

**Morning session: Topic III / 133**

## **An integrated modelling and measurement study to investigate co-condensation of organic vapours and water vapour in cloud droplet formation**



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The coupled system of the Manchester Aerosol Chamber (MAC) and Manchester Ice Cloud Chamber (MICC) can be used for detailed studies of cloud formation on specific aerosol particles. A bin microphysics model, pyACPIM, is specifically designed to be used in conjunction with cloud chambers to aid understanding of the cloud experiments. It is based on the underlying science of the Aerosol-Cloud and Precipitation Interactions Model (ACPIM) model and will be available on the EUROCHAMP-2020 website in the near future for the wider scientific community to use.

Here, we study the impact of semi-volatile particles on cloud formation: The process of cloud droplet formation by condensation of water vapour on cloud condensation nuclei is relatively well understood for non-volatile particles. However, particles suitable to act as condensation nuclei vary widely in volatility and may therefore be semi-volatile or volatile. In theory, co-condensation of organic vapours and water vapour increases cloud particle numbers, however observational evidence is lacking.

We present data from experiments carried out in the coupled chamber system MAC-MICC, with the aim of observing the effect of co-condensation of organic vapours on warm cloud formation, accompanied by model simulations of the chamber experiments with pyACPIM. We further show the general applicability of pyACPIM by simulations of cloud formation experiments using the well known particle systems ammonium sulphate and sodium chloride.

**Morning session: Topic III / 292**

## **Finding Closure - Why We Need Radar, Lidar and Solar Radiance Observations to Distinguish different Microphysical Regimes in Ice Clouds**

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One of the largest uncertainties in climate change predictions is still caused by ice clouds. They have a large direct effect on Earth's radiation budget since they reflect solar radiance into space and can trap thermal radiation within the atmosphere. The quantification of this process can be significantly improved by active remote sensing, which can explore vertical profiles of ice cloud microphysics. However, strong biases in ice water content and ice water path are to be expected for individual cloud regimes since most radar-lidar retrieval algorithms rely heavily on one mass-size relationship to parameterize the prevalent ice particle model. In many cases, these biases can be identified and corrected when a vertically integrated quantity, like the solar reflectance, is considered simultaneously.

Within the last years, great efforts were made during the NARVAL and NAWDEX airborne campaigns to acquire combined radar, lidar and solar reflectance measurements on a single platform to develop synergistic cloud retrievals. Within this context, the German research aircraft HALO was equipped with a high spectral resolution lidar (HSRL) system at 532 nm with additional polarization

sensitive channels at 532 and 1064 nm, a high-power (30kW peak power) cloud radar at 35 GHz, a microwave radiometer package and passive radiation measurements with the hyper-spectral imager specMACS.

In this study, we analyze HALO measurements in different synoptic regimes to retrieve ice cloud properties using the variational radar-lidar retrieval VarCloud. In addition, we use the retrieved ice cloud properties to simulate solar radiances, which we then compare to measured solar radiances from specMACS. The retrieval and forward simulations are done for different assumptions about the prevalent ice particle model. The objective of this closure study is the identification of inconsistencies of the currently used mass-size relationship. With respect to the radiative closure, modifications to the mass-size relationship are devised and checked with simultaneously acquired in-situ measurements. In doing so, this study will improve the understanding of ice cloud microphysics with respect to the prevalent ice particle model, which better replicates radar, lidar and solar radiance measurements. Finally, we will put these findings into the context of their synoptic and dynamic environment to reach-out to modeling communities.

**Morning session: Topic III / 240**

## Where is a cloud? - 3D cloud geometry from airborne imagery

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observe – model – compare – repeat

This general approach should also lead to a better Understanding of Clouds and Precipitation. Multiple large airborne field campaigns, including NARVAL, NAWDEX and EUREC<sup>4</sup>A have been and will be set out to basically create comprehensive snapshots of clouds and the atmosphere. A presumably simple question to ask from these snapshots – Where is a cloud? – is both, interesting on its own and the foundation for other retrieval methods. Albeit its simplicity, answering this question turns out to be rather difficult in practice.

During the NARVAL-II and NAWDEX field campaigns, we captured high resolution RGB images of a wide observation area using a calibrated 2D video camera which is part of the specMACS instrument. This camera yields a detailed view of the scene but, as opposed to active remote sensing, does not provide position information for the measurements directly. We present a stereographic method to derive cloud location and high-resolution top geometry information from these images and show the quality of the result by comparison to data from lidar. We will also show first results of cloud motion estimates, which have been obtained as a by-product of this method.

**Morning session: Topic III / 75**

## Understanding Tropical Mesoscale Life cycle through merged satellite observations

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Mesoscale deep convective systems (MCS) and the areally extensive anvils associated with them explain more than half of total rainfall in the wet Tropics. They are major source of diabatic heating that drives the Hadley and Walker circulation and because of their horizontal extent and duration (that further exceed the duration of convective towers), anvils affect the tropical energy balance.

MCS life cycle may be divided in three stages : initiation, mature and dissipation which involve different physical processes that impact both the hydrological and energy cycle. If General Circulation Models aim at representing the water and energy cycle evolution, an accurate representation of MCS and related processes is needed.

From an observationnal point of view, geostationary satellite images in which tracking algorithms can be applied are powerful tools to document the morphological evolution of MCS from their birth up to their collapse at the tropical scale. However insights on involved physical processes remain limited. This presentation shows how we can take advantage of orbiting satellites like TRMM, A-Train or Megha-Tropics for documenting microphysical, radiative and diabatic processes involved in the tropical MCS life cycle.

It is first shown that MCS life cycle at the scale of the Tropics is sharing common characteristics, independently of the geographical areas, the size, the life duration or the propagating nature of the MCS. Each life step, is then documented using observations from the orbiting satellites and results are contrasted as function of the environment.

This presentation will show that different microphysical processes are found in the convective, precipitating and non-precipitating anvils of the MCS and how the orders of magnitude differ between continental and oceanic MCS. Radiative properties throughout the life cycle evolves differently for continental and oceanic MCS, but large differences (in term of amplitude or evolution) are also found among the sampled regions. Diabatic heating (latent and radiative) is finally examined.

**Morning session: Topic III / 273**

## **The Ruisdael Observatory: a new facility for atmospheric research in The Netherlands**

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In the next decades, governments worldwide are planning to spend enormous amounts of public funds to cope with expected climate change. To effectively prioritize measures to be taken, there is an urgent need for reliable short term forecasts of weather, and to assess the effects of climate change on local extreme weather events – especially at a regional and local scale. Reliable predictions are however severely hindered by an incomplete representation of short-lived climate forcings and processes that operate in the climate system, and specifically their small-scale spatial and temporal variability. Present permanent facilities to study these processes lack the required ability to couple data and models at different spatial and temporal scales, and lack the capability for producing high resolution 3D information at the appropriate scales. The Dutch government has recently allocated funds to the new initiative of The Ruisdael Observatory with the aim of removing these barriers.

The Ruisdael Observatory will operate at the full scale of The Netherlands at the unprecedented spatial resolution of hundred meter. Considerable progress has been made on global atmospheric modelling, with resolutions approaching the 1 km and even 100 m scale. However, these atmospheric models are still too coarse, and not able to resolve crucial small scale phenomena, such as turbulence and cloud microphysics and the interaction with surface energy fluxes. The Ruisdael Observatory will merge observations and models in real time, at different spatial and temporal scales, to form a virtual laboratory for studying multi-scale processes in atmospheric chemistry and physics, and by doing so improve the accuracy of climate, weather and air quality models. By reducing the need for parameterizations, atmospheric models will increasingly be based on first principles of atmospheric physics.

The Ruisdael Observatory will consist of

- a nationwide ubiquitous network of sensors to measure the 3D physical and chemical state of the atmosphere and its interaction with the land surface,
- four advanced anchor stations: the already existing, rural, CESAR Observatory and a new urban station in Rotterdam, a coastal station and one in forestry.
- mobile facilities, including a mobile cloud profiler, an aircraft, drones and a measurement van for

aerosols and trace gases.

- a computational facility for real-time simulations of the atmosphere and its interaction with the surface.

Poster Session B / 40

## Mesoscale circulations and organized convection in African Easterly Waves

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Global convection-permitting model simulations and remote sensing observations are used to investigate the interaction between organized convection and the atmospheric circulation in the case of an African Easterly Wave (AEW). The wave disturbance is associated with a quadrupole structure of divergence, with two convergence centers slightly ahead of the trough. Moisture transport from southeast of the trough to the area in front, and lower mid-tropospheric moisture convergence precondition and organize convection. The main inflow into the squall line cluster is from behind. The moisture-abundant inflow collides at the low-level with high moist static energy monsoon air and establishes a frontal line of updrafts at the leading edge of the propagating mesoscale convective system. A mantle of moisture surrounds the convective core. Dry convection associated with the Saharan Air Layer (SAL) and SAL intrusions into the wave trough together with vorticity advection can play a role in intensifying AEWs dynamically as they move from the West African coast across the Atlantic ocean. Our analysis demonstrates that the synoptic-scale wave and convection are interlinked through mesoscale circulations on a continuum of scales. This implies that the relation between organized convection and the atmospheric circulation is intrinsically dynamic, which poses a particular challenge to subgrid convection parameterizations in numerical models. The work will also be set in the wider context of theories on the interaction between moist convection and the atmospheric circulation in the tropics.

Poster Session B / 125

## The Use of Sparse Field-Campaign Data to Configure LES in the Subtropical Atlantic

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Observed data, recorded during field campaigns conducted in regions where observations are generally scarce, can be used to make large-eddy simulations more representative of the local conditions. In this study, the Dutch Atmospheric Large-eddy Simulation (DALES) model is used to generate a set of 36 simulations. These simulations are generated at the locations of 11 dropsondes launched during the fourth Research Flight, conducted as part of the Next-generation Aircraft Remote sensing for Validation Studies (NARVAL) Campaign, on December 14th 2013. The 36 simulations are divided into a set of control experiments, a set of simulations with the dropsonde profiles blended into the GCM-derived large-scale forcings, and a set of sensitivity experiments. Two metrics have been used to study the impact of blending the dropsonde profile into the large-scale forcings. The first metric is designed to quantify the impact on the boundary layer deep structure. The second metric is a new probabilistic method designed to allow a fair statistical comparison of inversion properties between

point-measured observation soundings and 3-dimensional LES field. The 14 simulations generated as part of the sensitivity experiment are divided between three sub-categories: a) the nudging time-scale intensity, b) the length of the nudging time-window, and c) the vertical resolution of the LES. Results from these simulations indicate a strong evolution of the boundary layer on hourly time scales, which supports observations at the Barbados Cloud Observatory. The boundary layer deep structure is improved by including the dropsonde profiles in the large-scale forcings. On the other hand the impact, of nudging the simulation towards the dropsonde, on the inversion strength is less strong. The simulations are currently being compared to additional observations recorded by instrumentation on-board the High Altitude and Long Range Aircraft (HALO), including the Halo Microwave Package (HAMP), and will be discussed in the presentation.

## Poster Session B / 50

### Exploring the consequences of nearest neighbour interaction in convective parametrisations

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The goal is to gain some insight into the possible consequences of explicit treatment of organisation within a NWP model with parameterised convection. To this end we formulate a nearest neighbour coupling between grid points to implement a convective trigger that shows sensitivity to its surrounding conditions. The philosophy is based on 2D Lattice models and is inspired by the work in Ref. 1. We work with the global ICON model [2] at the operational grid point distance of thirteen kilometers. The implementation is rather ad hoc but is helpful to investigate the possible impacts on the structure of the precipitation field. In particular we compare to the storm-resolving simulation of the NARVAL case [3]. In addition we investigate the behaviour of the parametrisation over the maritime continent. It turns out, for example, that some organised structures that are lost within the standard parametrisation setup can be recovered with nearest neighbour coupling.

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## Poster Session B / 46

### The key processes in the overshooting convection that hydrate the stratosphere

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The key processes in the overshooting convection that hydrate the stratosphere

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Overshoots are convective air parcels that rise beyond their level of neutral buoyancy. A Giga Large-Eddy Simulation (100 m cubic resolution) of «Hector the Convecteur», a deep convective system that regularly forms in Northern Australia, is analysed to identify overshoots and quantify the effect of hydration of the stratosphere. In the simulation 1507 individual overshoots were identified and 46 of them were tracked over more than 10 minutes. Hydration of the stratosphere occurs through a sequence of mechanisms: overshoot penetration into the stratosphere, followed by entrainment of stratospheric air and then by efficient turbulent mixing between the air in the overshoot and the entrained, warmer air, leaving the subsequent mixed air at about the maximum overshooting altitude. The time scale of these mechanisms is about 1 minute. Two categories of overshoots are distinguished: those that significantly hydrate the stratosphere and those that have little direct hydration effect. The former reach higher altitudes, and hence entrain and mix with air that has higher potential temperatures. The resulting mixed air has higher temperatures and higher saturation mixing ratios. Therefore greater amount of the hydrometeors carried by the original overshoot sublimate to form a persistent vapor-enriched layer. This makes the maximum overshooting altitude the key prognostic for the parametrization of deep convection to represent the correct overshoot transport. The implication for a common parametrization of deep convection will be discussed.

#### Poster Session B / 77

### Assessment of the French cloud-resolving model AROME over the Caribbean domain

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The French cloud-resolving model (CRM) AROME (Seity et al., 2011) has been operational over the Caribbean domain, with a 2.5 km horizontal resolution, since February 2016. At this horizontal resolution, it is still a challenge to reproduce correctly the trade-wind cumulus, their cloud top and their associated trade-wind inversion temperature. The AROME assessment is based on observations available within the Caribbean domain: the super-site of Barbados Cloud Observatory (BCO). Radiosondes are used to document dynamical and thermodynamical bias and the Coral cloud radar of BCO is used to assess the ability of the model in simulating clouds as performed in Nuijens et al. (2015). The model behaviour is investigated in contrasted regimes: dry season (January/February) and the rainy season (July/August). Both periods show consistent dry and cold biases for different locations. The simulated distribution of cloud fraction with height shows a double peak in agreement with observations with a large occurrence of clouds of low cloud fraction at the top of the boundary layer and a lower occurrence of cloud of high cloud fraction near the inversion of temperature around 700hPa corresponding to deeper boundary-layer clouds. All these investigations aim at identifying areas of model improvement in representing boundary layer processing and at improving the quality of weather forecast.

The two years (from 2017) of AROME simulations over the Caribbean Domain provide a wide data base to go further on details on the assessment of the model (interannual biases, mesoscale cloud organization, correlation with SST etc.). It also consists in an interesting data set for documenting processes into various atmospheric regimes. Furthermore, during the EUREC4A campaign, AROME could help in airborne flight planification. .

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## Poster Session B / 271

## Sensitivity of resolved convection in the Atlantic Basin to modes of Atlantic SST variability

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One of the most important modes of variability over the tropical Atlantic basin is the Atlantic Meridional Mode (AMM). Its main features consist of a meridional dipole of sea surface temperature (SST) anomalies coupled to cross-equatorial low level winds that affect the position of the Intertropical Convergence Zone (ITCZ) and therefore, modify the rainfall patterns over neighbouring continents. In this study we investigate the relationship between precipitation and the AMM in observations and model simulations using different resolutions and different representations of moist convection.

From the observations, we isolate the strongest AMM events as those that exceed one standard deviation above and below the mean value of the AMM time series. As found in previous studies, the most consistent characteristics among all the events are observed over northern South America during March to May season. A positive (negative) AMM is related to a northern (southern) displacement of the ITCZ and more (less) precipitation over northern South America, whereas negative (positive) precipitation anomalies are typically observed near the coast of Northeast Brazil. Positive AMM events are more uniform among them, while negative events show more variability as the spatial distribution of the rainfall response varies considerably in some regions. Moreover, negative AMM events tend to produce greater precipitation anomalies than the positive AMM ones. The spatial rainfall pattern of the negative AMM also differs from the positive AMM over the eastern basin, as the dipole of precipitation anomalies is observed up 20°W and it is not clearly noticed over western Africa. Based on these so defined strong AMM events we build composites of SST patterns for the positive and negative AMM phases that we use to force simulations performed with the ICON model.

## Poster Session B / 283

## An improved double Gaussian closure for the subgrid vertical velocity probability distribution function

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The vertical velocity probability distribution function (PDF) is analysed throughout the depth of the lower atmosphere, including the subcloud and cloud layer, in four large eddy simulation (LES) cases of shallow cumulus and stratocumulus. Double Gaussian PDF closures are examined to test their ability to represent a wide range of turbulence statistics, from stratocumulus cloud layers characterised by Gaussian turbulence, to shallow cumulus cloud layers displaying strongly non-Gaussian turbulence statistics. While the majority of the model closures are found to perform well in the

former case, the latter presents a considerable challenge. A new model closure is suggested which accounts for high skewness and kurtosis seen in shallow cumulus cloud layers. The well-established parabolic relationship between skewness and kurtosis is examined, with results in agreement with previous studies for the subcloud layer. In cumulus cloud layers, however, a modified relationship is necessary to improve performance. The new closure significantly improves estimation of the vertical velocity PDF for shallow cumulus cloud layers, in addition to performing well for stratocumulus. In particular, the long updraft tail representing the bulk of cloudy points is much better represented, and higher order moments diagnosed from the PDF are also found to be greatly improved. However, some deficiencies remain owing to fundamental limitations of representing highly non-Gaussian turbulence statistics with a double Gaussian PDF.

#### Poster Session B / 218

### Catching Cold Pools – dense nets during FESSTVaL 2020

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Cold pools are formed by evaporatively cooled downdraft air that spread on the surface underneath precipitating clouds and play a key role for the development and maintenance of convection. The passage of a cold pool front a few minutes ahead of the precipitation is generally associated with rapid perturbations of temperature, air pressure and wind speed. The next generation of weather and climate resolution with mesh size in the order of 1 km or less can explicitly resolve cold pools. The dynamics of cold pools is arguably one of the most beautiful feature of these novel simulation. However, are these simulated cold pools realistic? We lack observational reference data as coarse operational networks miss cold pools or cannot capture their spatial network. Finer nets are needed!

Novel observational technique to capture submesoscale variability in the boundary layer, like cold pools or wind gusts, will be explored during the FESSTVaL (Field Experiment on Submesoscale Spatio-Temporal Variability in Lindenberg) in 2020 at the meteorological observatory Lindenberg close to Berlin. FESSTVaL is a joint initiative of all partners of the Hans Ertel Centre for Weather Research (HErZ).

We will present the cold pools related components of FESSTVaL. In order to sufficiently capture the size structure of cold pools, a dense network of ground base measurement stations will be deployed within a radius of approximately 20 km around the Meteorological Observatory Lindenberg for an extended summer period in 2020. The network will consist of about 100 low-cost and power-saving data loggers that autonomously record air pressure and temperature with a temporal resolution of 1 s and are currently developed and tested at the University of Hamburg. Analysis of routine observation data reveals that the negative temperature perturbation on average lies between 3 and 4 K while the pressure and wind speed anomalies mostly in the order of 1 hPa and 3 m/s, respectively – all these signal are well detectable. A coarse net of 20 present weather stations and a few high-accurate energy balance stations will complement this dense net. In addition, the potential of upcoming citizen science networks will be explored.

#### Poster Session B / 261

### How important is cloud phase for climate sensitivity?

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Reflectivity and lifetime of clouds may be enhanced when cloud ice changes to liquid water in a warmer climate. The spread in this cloud phase feedback in climate models adds to the spread in cloud feedbacks (and therefore equilibrium climate sensitivity, ECS). Although the global aerosol climate model ECHAM6-HAM2 underestimates the supercooled liquid water fraction (SLF) in mixed-phase clouds, we do not obtain increases in ECS in simulations with more supercooled liquid water in the present day climate. We find that it is low- and mid-level mixed phase clouds that are not shielded by higher-lying ice clouds, occurring most frequently in midlatitudes, which are important for the cloud phase feedback.

For further analysis in a newer model version of ECHAM6-HAM2, we introduced new model tracers for different freezing mechanisms at mixed-phase temperatures (i.e. between 0 and -35°C). These showed that the ice in mixed-phase clouds originates mainly from freezing at temperatures colder than -35°C (65% of cloud volume vs. 7% cloud volume originating from immersion and contact freezing in mixed-phase clouds). We find that only ice forming in the mixed-phase temperature range can contribute to the phase feedback while ice associated with thick clouds like nimbostratus or deep convective clouds (which contain most of the ice in the mixed-phase temperature regime in this model) does not contribute. Therefore the global SLF in a climate model is not a good indicator for the strength of the cloud phase feedback in a climate model.

**Poster Session B / 178**

## **Quantifying parametrized cloud-fraction errors and their scale dependence**

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The representation of unresolved clouds is a large source of uncertainty in atmosphere circulation models, but it is difficult to quantify the specific error contributions of individual parametric components, such as cloud macrophysics and cumulus entrainment. A widely used approach to determine the individual parametrization errors is to use large eddy simulation (LES) data as a representative proxy atmosphere against which the parametrizations can be evaluated. A drawback of this approach was that until recently LES simulations were commonly limited to small domains and highly idealized prototype situations. However, there are now super-large-domain realistically forced simulations available which contain previously excluded synoptic scale variability and orographic effects. We use such simulations covering Germany at a 100 m resolution to quantify the errors introduced by two cloud fraction parametrizations, one a classic relative humidity parametrization and the other based on a probability density function of total water. We will focus on the horizontal scale-dependence of the parametrizations to determine for which model resolutions the parametrizations are suited. We do this by means of a subdomain analysis, i.e. cutting the full LES domain into subdomains of varying size before the cloud fraction parametrizations are applied and evaluated against each vertical layer. Lastly, we will show how the results of the large-domain LES analysis can be used to improve the parametrization performance.

**Poster Session B / 161**

## **Cloud microphysics development and evaluation for simulating mesoscale convective systems in global models**

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Mesoscale convective systems (MCSs), one of the most climatically significant forms of convection, influence the climate system through affecting energy and water cycles.

State-of-the-art GCMs cannot well simulate many aspects of MCSs, including initiation, propagation, cloud phase, heating, and diurnal cycles of temperature and precipitation. The Great Plains of the U.S. provide an excellent venue for studying continental long-lasting and propagating MCSs. Our major goal is to develop treatments of convection and microphysics capable of representing MCS features in the US Department of Energy (DOE) newly-developed global model – the Energy Exascale Earth System Model (E3SM). We have coupled a new cloud microphysics scheme that has the advanced representations for ice microphysics particularly associated with riming – the Predicted Particle Properties (P3) into E3SM and the Multiscale Modeling Framework (MMF) of E3SM, since representation of rimed particles is important for MCS simulations. The results show a significant improvement in simulating heavy precipitation rates. However, large discrepancies in precipitation compared to observations still exist. We find that model resolution plays a significant role in capturing MCS initiation convection upscale growth processes. By using either a regional refinement grid (RRM) at  $\frac{1}{4}$  degree over the contiguous United States (CONUS) or a refined host model grid-spacing (1 degree) in MMF-E3SM, the simulations are able to capture several major MCS events in May 2011. But the underestimation of heavy precipitation is still present. We will discuss the factors contributing to the underestimation, for example, the dry biases in simulated low-level jet and the failure to capture the upscale growth.

## Poster Session B / 96

### Local and remote controls on Arctic Mixed Layer evolution

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Air mass exchanges between the Arctic and mid-latitudes play an important role in Arctic Amplification. What controls the transformations of such air masses is not yet fully understood. Local processes affecting air masses include vertical mixing, surface exchange processes and cloud formation. On the other hand, large-scale dynamics can also affect air masses, for example through subsidence. This study aims to gain insight by combining observations made during the (AC)<sup>3</sup> PASCAL field campaign in May-June 2017 with targeted experiments with the Dutch Atmospheric Large-Eddy Simulation model (DALES). A Lagrangian framework is adopted, following warm and moist air masses as they move towards the PolarStern Research Vessel. This allows the simulated Arctic Mixed Layer (AML) including clouds to evolve freely over a significant time-period. Eight air masses are simulated as observed between 5-7 June 2017, when the PolarStern was located in the sea ice north of Svalbard. The air masses intersect with eight radiosondes launched during this period. A number of problems had to be overcome in configuring the cases, including i) a lack of upstream information and ii) biases in the IFS analysis data used to force the simulations. To this purpose the forcings and initial profiles were adjusted under certain constraints. An iterative approach relying on microgrids was employed to obtain the case configuration that yielded the best agreement with the radiosonde data. A key novelty is that time-dependent forcing is applied, maintaining full variability in large-scale signals like subsidence. Key features of the cloudy AML are reproduced with this setup. A first group of 12-hour simulations without surface coupling reproduces the capping humidity layers observed during this period. A second group of 60-hour simulations maintains surface coupling, designed to identify local and remote controls on the evolution of the cloudy AML. A mixed-layer mass budget analysis reveals that cloud-top cooling driven entrainment continuously adds mass in a fairly

time-constant way. Large-scale subsidence counters this effect, but shows considerably more time-variation in sign and amplitude. Subsidence thus effectively controls the time-evolution of mixed layer deepening. Strong subsidence events can even cause cloud collapse, significantly affecting the surface radiative budget.

#### Poster Session B / 200

### A COOKIE for climate change?

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Cloud-radiative interactions are an important factor for the response of the large-scale circulation to global warming. Two approaches have been put forward to study the radiative impact of clouds in global climate models. The COOKIE method makes clouds transparent to radiation. The cloud-locking method prescribes the radiative properties of clouds to either the present-day or global-warming conditions. The cloud-locking method successfully quantifies the contribution of cloud-radiative changes to the model-projected circulation response. However, the method requires fairly substantial model modification and a large set of prescribed-cloud simulations. In contrast, the COOKIE method is easy to implement and requires only two simulations with transparent clouds. This raises the question if the COOKIE method can be used to study the impact of cloud-radiative changes on the circulation response to global warming.

Here, we compare the COOKIE method to the cloud-locking method in the three global climate models MPI-ESM, IPSL-CM5A and ICON, and in simulations with aquaplanet and present-day boundary conditions. We find that while cloud-locking diagnoses a robust poleward circulation expansion due to cloud-radiative changes, COOKIE fails to capture this impact. In particular, COOKIE does not capture the cloud-radiative impact on the response of the Hadley cell width and strength, and on the poleward extent of the subtropical dry zones. The discrepancies are somewhat smaller in the extratropics. COOKIE qualitatively captures the cloud-induced poleward shift of the jet stream, but it tends to strongly estimate the cloud impact. We argue that the lack of success of the COOKIE method results from large differences between the clouds-on and clouds-off control climates, and the fact that COOKIE includes radiative changes of water vapor.

Our results show that COOKIE, while being a valuable tool to understand the impact of clouds on the present-day circulation, it should not be used to study the impact of cloud-radiative changes on the circulation response.

#### Poster Session B / 190

### Harmonizing cloud-related schemes at grey zone resolution in operational NWP

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The introduction of the resolved-signal-sensitive deep convection scheme CSD (Complementary Sub-grid Draught scheme, Gerard 2015 - an approach that is one step forward beyond being simply 'scale-aware') in the Alaro operational NWP model revealed some weaknesses in other parts of the model physics, that lead it to degrade the model scores compared with the previous 3MT (Gerard et al. 2009) scheme.

The CSD scheme tries to produce a signal complementing the part of the subgrid updraughts that are

partially resolved at grey-zone (convection-permitting) resolutions. This renders the scheme generally much less active at fine resolution than the 3MT scheme, especially in winter, where the latter still brought a substantial contribution to cloud and precipitation.

The model was using two separate cloud representations, with prognostic water variables for thermodynamic and microphysical processes, but re-estimating the clouds diagnostically from total water and local saturation for radiation calculation and model output.

The challenge was to be able to produce, through the joint behaviours of the cloud scheme and the subgrid convection scheme, the same thermodynamical processes at the same location as before, despite the dramatic change in the respective amplitudes and vertical distributions of the two contributions; and at the same time, generate similar cloud amounts, directly from the prognostic cloud scheme (unified cloud representation).

When deep convection is partly resolved, the statistical cloud scheme, primarily aimed at representing stratiform clouds, has to become able to also represent adequately the resolved part of the subgrid convective updraughts.

Our revised cloud scheme associates Smith (1990) and Xu and Randall (1996) proposals for stratiform clouds and further makes the cloud fraction also depend on the resolved updraught.

Combining this 'stratiform+resolved cloud' fraction with the subgrid convective cloud fraction yields the total cloud.

Including effects of the subgrid convective signal on the auto-conversion and collection processes in the microphysics further allows to reinforce convective precipitation and induces various feedbacks on convective condensation and cloud.

The complete scheme with much more consistent re-unified cloud representation and CSD allowed to recover satisfying model scores, while benefiting from the finer simulation of the precipitation areas and the multi-scale behaviour provided by CSD.

## Poster Session B / 102

### Evaluation of bulk mass-flux formulation in convection parameterization using large-eddy simulations

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In this study, the bulk mass-flux formulation is evaluated for both shallow and deep convection using large-eddy simulations of BOMEX and radiative convective equilibrium (RCE) cases. The bulk mass-flux approximation under-estimates the total vertical fluxes even though the evaluation uses the extreme velocity values that control the vertical transport effectively. The inter-plume variability and intra-plume variability are comparable but generally do not share similar shapes with each other or with mass-flux term, and thus could not be simply parameterized with rescaling. In the sub-cloud layer, environmental intra-plume variability accounts for most of the vertical fluxes. Possible solutions have been proposed to maximize the contribution from bulk mass-flux formulation. The inter-plume variability could be eliminated by a spectrum or a multi-plume representation. An analysis of spectral representation shows that the intra-plume variability of buoyancy flux for plumes with medium sizes (400-600 m) is still non-negligible and thus needs to be parameterized. A multi-plume analysis confirms that a two-plume representation, that is, a weak and a strong plume for both updrafts and downdrafts, could effectively suppress the intra-plume variability. As a result, the two-plume model improves the representation of total vertical fluxes with the mass-flux approximation in the cloud layer. Therefore, we propose a core-skirt representation for convection and the parameterization could inherit from the conventional mass-flux framework.

## Poster Session B / 212

## Some superparameterized hindcasts of the MJO

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Hindcasts of an ensemble of past MJO events were performed using a superparameterized version of the global WRF model under specified SST conditions. Results show that the model skill is importantly sensitive to microphysical parameter settings that control the efficiency of warm rain production, with skill being generally improved under either a) halving of the accretion efficiency of cloud water by rain or b) doubling of the efficiency of rain water evaporation in unsaturated air. The change in skill is found to be comparable to that of specifying time-varying vs time-invariant SSTs. A budget of moist-static energy is used to explain these findings.

### Poster Session B / 124

## Title: ICON simulations of cloud-diabatic processes in a warm conveyor belt of an extratropical cyclone: A case study

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Extratropical cyclones are related with various diabatic processes occurring in clouds such as latent heat release, cloud-radiative interactions and precipitation. A majority of these processes in cyclones occur within a coherent stream of air masses known as the warm conveyor belt (WCB). Accurately representing these WCB processes in models is important for predictions of extratropical weather phenomena. In this contribution, we focus on the ascending part of WCB. For this purpose, storm resolving simulations with the ICON model are applied to investigate a specific case from the NAWDEX campaign - cyclone Vladiana - that occurred on 23rd September, 2016. Using increasing horizontal resolution from 80 to 2.5 km over a domain extending from 78W-40E and from 23N-80N and with 1- and 2- moment cloud microphysics, different simulations are carried out to test the sensitivity of cloud radiative effects, cloud fraction and cloud phase to resolution and model physics in WCB cross sections. The results will be further compared with observation from the NAWDEX field campaign for a better understanding of model weaknesses, strengths and uncertainties.

### Poster Session B / 136

## LES simulations of stratocumulus: why so sensitive to model setup ??

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Large Eddy Simulations (LES) are considered a “tool of choice” for numerical simulations of many boundary layer clouds. It is believed, that LES resolution is good enough to capture the most important effects of turbulence and entrainment, while present computer resources are effective enough

allow to simulate mesoscale (order to kilometers or more) features of clouds and cloud fields. However, when applied to stratocumulus clouds, simulations hardly converge. Slightly different setup may result in very different cloud on the output. Sometimes e.g. increase of grid resolution leads to nonphysical cloud dissipation.

In the presentation we will discuss results of LES simulations of stratocumulus clouds based on experimental data from DYCOMS-II and POST field campaigns. We will focus on entrainment of free tropospheric air into the cloud as a key physical mechanism governing cloud growth/decay and argue, using analysis of the experimental data, that typical resolutions of present LES are not enough to properly simulate entrainment dynamics. In effect non-physical properties of simulation setup, like gridbox aspect ratio or subgrid scale parameterization of turbulence govern entrainment in the virtual reality of numerical clouds.

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**Poster Session B / 143**

## **Combining dual-frequency radar and microwave radiometer for improved water vapor profiling in the cloudy atmosphere**

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The accurate automatic measurement of water vapor in the lower troposphere still remains a challenge despite satellites and radiosonde networks due to low spatial and temporal resolution. Remote sensing ground-based measurement sites, such as the Jülich Observatory for Cloud Evolution (JOYCE) and the Barbados Cloud Observatory (BCO), have the potential to fill in this gap, providing 24/7 measurements with high temporal resolution. Combining the information from active and passive instruments, for example radar and microwave radiometer, can improve the information content of humidity profile retrievals.

The presented synergistic retrieval algorithm retrieves Liquid Water Path (LWP) and partially Integrated Water Vapor (IWV) below and within single-layered liquid water clouds, as well as the exponential decay of absolute humidity above these clouds typical for the Atlantic trade wind region. We use the microwave radiative transfer model PAMTRA to simulate synthetic observations in 7 water vapor sensitive microwave radiometer channels, and the differential wavelength ratio (DWR) of the radar reflectivities at 35GHz and 94GHz. Including the active observations increases the information content by 0.9 degrees of freedom from 2.6 to 3.5, and decreases the retrieval error of each parameter by 10%-40% compared to an application using only passive observations. The

retrieval is applied to first case studies based on the observations at BCO including the new 94GHz radar, using simultaneous radiosonde ascents for retrieval evaluation purposes.

Poster Session B / 228

## A New Generalised Mass-flux Convection Scheme for the Met Office Unified Model

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A new convection parameterisation is being developed under the ParaCon project (a joint research effort on convection by the UK's Met Office and NERC). The new convection scheme code flexibly incorporates a wide range of scientific developments within the "mass-flux" framework:

- Spectral cloud model option (many convection types in parallel).
- Updrafts and downdrafts may trigger from any height in the same way, permitting multiple convective layers in a column, each simulated using the same scheme.
- Thermodynamically-consistent formulation which accurately conserves heat, moisture and momentum.
- Phase-changes and precipitation processes are modelled using a simple mixed-phase microphysics scheme called within the updrafts and downdrafts, with a robust numerical method to implicitly solve the Bergeron-Findeisen process.
- Vertical momentum budget for unresolved convective thermals, coupled consistently to the resolved-scale vertical velocity, for use in the grey-zone.
- Adaptive entrainment and detrainment, coupled to the vertical momentum equation.
- Simulation of the expected horizontal scale of the unresolved part of the updraft spectrum, and the effects of this on entrainment and updraft dynamics.
- Scale-aware, stochastic triggering formulation which naturally deactivates the parameterised convection when the turbulent eddies responsible for triggering convective clouds are expected to become resolvable.

This scheme is used to explore the sensitivity of convective organisation in the Unified Model to the representation of thermodynamics, microphysics and dynamical processes in the parameterised updrafts and downdrafts.

Updrafts rising through a pre-existing deep convective cloud system glaciate at a lower altitude than newly initiating convection, due to "seeding" by ice falling into the rising thermals from above. This allows the former to be more buoyant than the latter near the freezing level inversion, favouring ascent in pre-existing cloud systems over new initiations. We investigate whether representing this process in the convection scheme may improve the realism of convective organisation in convection-parameterising models.

Poster Session B / 117

## How wind shear keeps shallow cumulus clouds shallow and modulates their momentum transport

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Motivated by the uncertain role of trade wind cumulus in GCM predicted climate change and an apparent observed relationship between low cloud cover and surface wind speed, our study focuses on how shallow cumulus convection and horizontal winds in the trades interact and how such an interaction might matter to large scale circulations. We first evaluate how wind shear affects shallow convection and then focus on understanding its momentum transport.

Using DALES, we simulate idealized cases for shallow cumulus and congestus clouds typical of the subtropics imposing varying large-scale zonal wind shear on increasingly large domains (up to 50 x 50 km<sup>2</sup>). We first show how shear influences convection and cloudiness. Most prominently, we observe that clouds grow less deep in the presence of shear and are accompanied by marginally weaker convective updrafts. This leads to a shallower and moister trade wind layer. The higher relative humidity in the sheared trade wind layer results in an increased cloud amount near cloud base. We hypothesise that wind shear distorts aggregated moist regions and coherent updrafts/downdrafts in the subcloud and lower cloud layer.

In our simulations, cloudy volumes generally have lower (horizontal) wind velocities than clear sky volumes, as updrafts carry air with lower momentum from near the surface upwards. Further, we observe significant variations in winds at the outer cloud edges depending on the imposed shear. Even in the surface layer we find significant wind variability associated with cold pools, which have markedly different characteristics depending on the background shear. In this presentation, we will explain these changes in horizontal winds and show the impact of total and convective momentum transport.

In addition to rather idealized simulations, we investigate how robust our results are when moving towards more and more realistic settings. This includes not only the dependence on domain size but also different radiative transfer. Additionally, we consider simulations of single days of the NARVAL-I and NARVAL-II flight campaigns ran with the ICON-LEM over a large portion of the North Atlantic.

**Poster Session B / 110**

## **New Particle Formation and Aerosol Variability Near Southern Ocean Low Clouds**

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The largest uncertainty in the first indirect effect is knowledge of the pre-industrial aerosol state. The Southern Ocean (SO) offers a remote and pristine environment that is the closest, measurable analog to this pre-industrial environment. The SO is also rich in low clouds, which are prevalent in the cold sectors of cyclones. Sampling the natural aerosol in this environment, and understanding how cloud properties depend upon them, will provide a baseline for the aerosol indirect effect. In-situ observations of low clouds and aerosols in the SO have been limited due to the remoteness of the region.

However, the recent Southern Ocean Cloud Radiation Aerosol Transport Experimental Study (SOCRATES) sampled clouds and aerosols across a range of meteorological environments in January and February 2018. In-situ ship and aircraft measurements were made between 45 and 62°S with a focus on



observing clouds and aerosols occurring in cyclone cold-sectors. Throughout the campaign, evidence of recent new particle formation was observed in the free troposphere and in the above cloud sampling. This contributed to unusually high concentrations of condensation nuclei (>1000/cc of particles larger than 10 nm) observed in the SO compared to other low cloud regions of the world (e.g. SEP, NEP, and NEA).

In this work, we propose a mechanism for production of new particles in the SO associated with cyclonic ascent. We also suggest connections with the accumulation mode aerosol population and the relatively common occurrence of high cloud droplet number concentrations greater than 100/cc in low-lying SO clouds. SOCRATES measurements are combined with HYSPLIT trajectories and reanalysis products from ECMWF ERA5 and MERRA2. Nudged hindcasts from the Community Atmosphere Model (CAM6) and the Geophysical Fluid Dynamics Laboratory Atmosphere Model (AM4), both of which include prognostic aerosols, are used to examine the proposed new particle production mechanism and to determine the current limitations of model aerosols.

Poster Session B / 237

## Does precipitation over the ocean scale with SST according to Clausius-Clapeyron?

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The capacity of the atmosphere to hold water increases with its temperature. According to the Clausius-Clapeyron (CC) relation, the atmospheric water content is expected to rise by about 7% per degree of warming, depending on temperature. However, for precipitation, changes in the upper percentiles have been found to follow or even exceed the CC-relation. Most of these studies focus on precipitation over land. Therefore, we investigate the scaling of oceanic precipitation to a change in sea surface temperature (SST). For that, we exploit two novel state-of-the-art datasets. First, the Ocean Rainfall And Ice-phase measurement Network (OceanRAIN) collects data from optical disdrometers onboard research vessels. Second, we use the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis version 5 (ERA5) at hourly resolution. While OceanRAIN allows a detailed view on precipitation along ship tracks at high spatiotemporal resolution, ERA5 adds a uniform global coverage as well as vertical velocity information. With seven years of data from OceanRAIN and ERA5, we analyze the influence of resolution, vertical velocity as an indicator for atmospheric circulation and data sampling on the scaling of precipitation (upper) percentiles with a change in SST over the ocean.

Poster Session B / 153

## Namib Fog Life Cycle Analysis - NaFoLiCA

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This presentation introduces the Namib Fog Life Cycle Analysis (NaFoLiCA) project. The life cycle of Namib-region fog and low clouds, as well as the factors driving their development are studied jointly by groups in Germany and Switzerland with partners in Namibia in a three-year effort.

In the hyperarid Namib desert low clouds and fog are a defining element of the hydrological cycle as well as the radiation balance. Due to a lack of observations little is known to date on the dynamics and drivers of this phenomenon. In NaFoLiCA we combine in-situ observations with satellite-based remote sensing and numerical weather prediction to understand the processes and their effects on the system scale.

In a field campaign conducted in September 2017 we observed profiles of fog events in a location near the coast and another further inland, complemented by meteorological and hydrological observations on a network of sites. These observations have helped improve satellite-based retrievals of fog and low clouds and their properties. Geostationary satellite data, complemented by active sensor information, is evaluated based on newly developed algorithms including concepts of computer vision. Numerical weather prediction is informed by insights gained from the in-situ observations and evaluated on the satellite product.

#### Poster Session B / 85

### Impacts of ice formation on cloud field organization - a case study of Arctic mixed-phase clouds

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In this study, we explore the impact of ice formation on cloud field organization in Arctic mixed-phase clouds using the COSMO model designed for idealized large eddy simulations (LES). It has been shown that cloud self-organization in boundary layer stratocumulus regimes and transitions between regimes can significantly alter the cloud radiative properties of the entire cloud field. Such transitions are governed by a variety of environmental factors such as tropospheric moisture content, large-scale subsidence, surface temperature or the ambient aerosol concentration. Each of these factors may impact precipitation formation, turbulence and boundary layer stability, and therefore cloud organization.

In the mid and high latitudes self-organized cloud structures have been attributed to frontal systems in low pressure systems or cold air outbreaks. However, cloud patterns are also observed away from these large-scale phenomena in the higher latitudes. As low-level clouds in the high latitudes are mostly mixed-phase, various processes can shape cloud formation, occurrence and break-up. Processes related to the ice phase remain poorly understood and especially with regard to cloud organization remain largely unexplored.

To gain first insight into cloud organization in mixed-phase clouds, we employ high resolution LES designed for the springtime Aerosol-Cloud Coupling and Climate Interactions in the Arctic (ACCA-CIA) campaign in the central Arctic. In a sensitivity study, we investigate the importance of the ice phase in mixed-phase clouds for the development of cloud cell structures, extent and regime transitions. In this regard, we test our hypothesis that ice processes may impact cloud organization by altering the cloud-base precipitation rate and potentially impacting the strength and extent of cold pools in the sub-cloud layer, both of which are deciding factors determining the length-scale of organization.

#### Poster Session B / 291

### How is a single updraft influenced by other clouds in a convective ensemble?

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Mass flux parametrisation schemes consider bulk cloud properties across a whole cloud ensemble, often without accounting for interactions between the clouds themselves. These interactions may be important for determining the growth of a single updraft, through widespread atmospheric stabilisation and moistening, or through dynamical modification of the boundary layer.

These interactions are investigated using high-resolution large-eddy simulations based on an observed case study of a convergence line over southwest UK. In the first simulation, a homogeneous surface heat flux produces a convective cloud ensemble, from which a representative cloud C1 is chosen using the cloud tracking algorithm of Heus and Seifert (2013). In the second simulation, a localised heat flux is used to produce a single cloud C2 in such a way that it is comparable to cloud C1, without the influence of the surrounding clouds. Differences in bulk quantities such as cloud top height, updraft speed and dilution between C1 and C2 are then quantified, and analysed in order to attribute these differences to atmospheric stabilisation and moistening, and dynamical modification of the boundary layer.

**Poster Session B / 310**

## **Scaling of extreme hourly precipitation in a pseudo global warming experiment with a convection permitting model**

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It is widely recognized that rainfall extremes intensify as the climate warms, yet the rate at which this occurs remains highly uncertain. Commonly, increases in precipitation extremes are linked to the Clausius-Clapeyron (CC) relation, which states that the maximum water vapour content of the atmosphere increases by 6-7 % per warming degree. Based on this rationale, methods have been employed in which the dependency of precipitation extremes on near-surface (dew point) temperature is derived from day-to-day variability in the present-day climate. Using this scaling approach, rates have been found exceeding the CC relation (super-CC) even up to twice the CC rate (2CC). However, a number of recent papers have challenged i) the applicability of the scaling approach in a long-term climate change context and ii) the realism of the climate change response exceeding the CC relation. Here, we show that – despite the obvious limitations of the scaling method – it does provide a reasonable estimate of the long-term trend due to thermo-dynamical processes. In a pseudo-warming experiment with a convection permitting model over Western Europe, whereby we fixed the large-scale circulation, scaling rates over land approximate 11-12 % per degree, well exceeding the CC relation, and matching those derived from the differences between a control experiment and a two-degree warmer experiment

**Poster Session B / 169**

## **The influence of shallow convection on wind profiles and wind variability in the mid-latitudes**

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Convective momentum transport (CMT) is an acknowledged process for deep convection, but still little is understood about how CMT shapes the cloud and sub-cloud wind profiles, and influences the circulation. This is even more true for shallow convection, for which only few studies explored the sensitivity of CMT on wind shear and how CMT may be parameterized (Brown, 1999; Schlemmer et al, 2017).

I will present a study on CMT in stratocumulus-to-cumulus topped boundary layers in an idealized Cold Air Outbreak case, where wind shear is significant.

Data is obtained via Large Eddy Simulations performed with the Dutch Atmospheric LES (DALES). The domain is  $96 \times 96^2$  in the horizontal and 5 in the vertical direction. A time varying increasing SST is prescribed to mimic a Lagrangian system that moves southward. The three simulations only differ in the prescribed wind shear: a case with Forward Shear FS (with absolute wind increasing with height), Backward Shear BS (decreasing with height) and No Shear NS.

The predominant effect of wind shear is to change the near-surface winds via momentum transport. The surface winds are reduced by around 1, 2.5 and 3.5 / in the FS, the NS and the BS respectively. The Coriolis force along with the large-scale pressure gradient produces inertial oscillations that affect the magnitude and angle of the wind. This changes the surface fluxes, which in turn leads to deeper boundary layers and a faster break up of stratocumulus under a FS profile.

The transition from stratocumulus to cumulus is also affected by wind shear in runs where the surface fluxes are held fixed, caused by greater shear-driven TKE production near the inversion under the FS profile, which maintains the largest wind speed jump across the inversion.

Small-scale turbulent transport is responsible for the overall drag effect of momentum transport (a downgradient momentum transport that leads to better mixing).

But 3D fields of the momentum flux clearly illustrate that momentum fluxes are substantially larger in (more confined) regions where strong updrafts and cumulus exist. By conditionally sampling and filtering out small scales, we show that in regions of convective circulations the momentum transport acts to enhance the flow in its prevailing direction, rather than slowing it down.

**Poster Session B / 276**

## **Hadley Cell expansion as a major contributor to GCM Southern Ocean cloud radiative effect variability and climate sensitivity**

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A recent investigation using satellite observations and reanalysis data found consistent positive relationships between poleward shifts in Hadley Cell (HC) extent and high cloud cover, statistically significant in nearly all regions and seasons. Over the lower-midlatitude region of the Southern Ocean, those cloud shifts are associated with weak shortwave radiative cooling. In contrast to observations, most CMIP5 GCMs show strong Southern Ocean SW radiative warming with poleward HC shifts in their control simulations, and the magnitude of the bias in model HC-SWCRE co-variability is related to model biases in climatological HC edge latitude and subsidence dynamics. Models with narrower Hadley Cells exhibit weaker lower-midlatitude climatological subsidence but larger subsidence increases with poleward HC shifts, resulting in more lower-midlatitude SW radiative warming. In climate warming simulations, where all CMIP5 models exhibit Hadley Cell poleward expansion, the models with the narrower climatological Hadley Cells produce stronger lower-midlatitude SW warming that contributes to higher Equilibrium Climate Sensitivity (ECS). This mechanism of control

of the radiative balance of the lower-midlatitude region by the climatological HC extent through subsidence dynamics was verified through a sensitivity analysis of aqua-planet GCM simulations. Here, the relationship between HC extent and the strength and width of the ITCZ is added to the investigation, in order to formulate a more complete depiction of Hadley cell effects on cloud radiative balance variability.

#### Poster Session B / 185

### Characterization of the spatial distribution of cumulus cloud populations using large-domain LES

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One of the challenges of present day climate and weather prediction modeling is the so-called grey zone problem. Due to the ever increasing efficiency of high-performance computers cumulus convection gets partially resolved. In response to this problem there is a focus on developing scale-aware parameterization schemes for boundary layer-scale processes, such as the formation of shallow cumulus clouds. To inform these new schemes, our ability to describe shallow cumulus cloud populations in terms of size and spacing needs to improve. Studying the spatial distribution of shallow cumulus clouds is not new, there are many studies on cloud size distributions and cloud organization. Early research used mainly satellite data to gain insight in the organization of clouds. Clustering of clouds was often found, as well as a relation between the size of clouds and their spacing. However, for reliable statistics on cloud populations the amount of data was too limited, since often only a few snapshots were available for analysis. Nowadays we have powerful computer models to our disposal which we can use to advance the research on the spatial distribution of clouds. For the current study we use data from an ICON simulation that is done over the tropical Atlantic, a location known for the regular occurrence of shallow cumulus. As added benefit this location has homogeneous surface conditions which enable us to ignore possible effects of the surface. The simulation consists of 4 nested domains, we use the inner domain with a resolution of about 150 m and a size of 150x400 km. This big dataset is used to quantify the spatial distribution of the clouds. Several metrics that are able to express irregularity are applied. Some are known (e.g. SCAI and radial distribution functions), whereas others originate from different scientific fields and have not been applied this way yet (hierarchical clustering). All results are normalized by a spatially homogeneous field, making it possible to compare the outcome of the different metrics. This comparison gives the opportunity to establish which metric would perform best in informing scale-adaptive parameterization schemes on the irregularity of cumulus convection.

#### Afternoon Session: Topic IV / 193

### Cloud-circulation coupling in the tropics and extratropics

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Clouds are an intrinsic part of the atmospheric circulation and its response to climate change. In this talk, I will review recent work on the importance of clouds and their radiative interactions for the tropical and extratropical precipitation and circulation. This includes the impact of the presence of cloud-radiative interactions on tropical precipitation and the midlatitude jet streams, which have been studied by making clouds transparent to radiation (the so-called COOKIE approach). This work

has demonstrated that cloud-radiative interactions narrow the ITCZ, strengthen the Hadley cell and weaken idealized midlatitude cyclones, and has shown that tropical and midlatitude clouds have opposing impacts on the position of the midlatitude jet. I will further cover the role of changes in cloud-radiative interactions for the circulation response to increasing surface temperatures. This work has benefitted from the cloud-locking approach, and has in particular identified high-level tropical and midlatitude clouds as drivers of future circulation changes. Overall, a growing body of literature points to an important but often model-dependent role of clouds for the midlatitude circulation, calling for a better understanding of the cloud-radiation-circulation coupling.

**Afternoon Session: Topic IV / 122**

## **Role of global versus regional cloud-radiative changes on the global warming response of the North Atlantic jet stream**

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Clouds and the mid-latitude circulation are strongly coupled via radiation. We investigate the impact of global and regional cloud-radiative changes on the global warming response of the eddy-driven jet stream in the North Atlantic. To this end, we perform global simulations with the atmospheric component of the ICOSahedral Nonhydrostatic (ICON) model, which is run with the physics package developed for numerical weather prediction. We prescribe sea surface temperatures (SSTs) to isolate atmospheric cloud-radiative effects, and mimic global warming by a uniform 4K SST increase. We apply the cloud-locking method to estimate the impact of cloud-radiative changes on the circulation's global warming response. This method allows us to break the cloud-radiation-circulation coupling and to investigate the total circulation response and the contributions of cloud-radiative changes and the SST increase.

In the first step, we estimate the impact of global cloud-radiative changes on the North Atlantic jet stream response. The North Atlantic jet stream shifts poleward and strengthens in response to global warming. About half of the annual-mean jet stream response can be attributed to the cloud-radiative impact. While the cloud-radiative impact varies little from season to season in absolute terms, its relative importance changes over the course of the year.

When globally imposing cloud-radiative changes, the largest cloud-radiative forcing is found in the upper troposphere over the Maritime Continent and the western tropical Pacific. Previous studies found that increased temperatures over the Maritime Continent can influence the North Atlantic jet latitude. We investigate the impact of regional cloud-radiative changes over the Maritime Continent on the global warming response of the North Atlantic jet stream. In addition, we analyze the impact of local cloud-radiative changes over the North Atlantic on the jet stream response. This enables us to investigate whether the cloud-radiative impact on the North Atlantic jet stream response is dominated by remote cloud-radiative changes over the Maritime Continent or by local cloud-radiative changes over the North Atlantic.

**Afternoon Session: Topic IV / 254**

## **Are clouds key to climate variability? Results from cloud locking in CESM**

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Clouds are intricately linked to the circulation in which they are found, making it difficult to disentangle the role of clouds in the flow without fundamentally altering the background state. One method that has proved useful in this regard is cloud-locking, whereby cloud parameters are prescribed to the radiation code of a numerical model, effectively decoupling the cloud radiative effect from the predicted flow. In this work, we apply cloud-locking to climate simulations with the Community Earth System Model (CESM) to explore how cloud radiative effects impact the climate across scales. The prescribed cloud data is derived from an independent CESM simulation, helping to preserve the mean climate state in the locked simulations. We describe the effect of removing interactive cloud radiative effects on a number of phenomena, including the position and strength of storm tracks, the behavior of the Madden-Julian Oscillation and other intraseasonal tropical disturbances, and the character of ENSO variability. In addition to fully-coupled simulations, we perform prescribed sea-surface temperature simulations to establish the role of cloud radiative effects on air-sea coupling. Some methodological aspects of cloud-locking will be discussed to illustrate how some subtle details can strongly impact the result while other choices seem to have little impact on the interpretation.

**Afternoon Session: Topic IV / 183**

## **A physical mechanism for the relationship between low-level cloud feedback and double-ITCZ bias.**

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Tian (2015) noted that climate models with more realistic simulations of the ITCZ/SPCZ tend to have higher climate sensitivities, and suggested that this might form the basis of an ‘emergent constraint’ which would rule out lower values of climate sensitivity. However, no physical mechanism has been proposed to explain this relationship.

Here we demonstrate that the width and intensity of the split/single ITCZ in the HadGEM2-A aquaplanet configuration can be controlled by varying the amount of longwave cloud heating in the atmosphere. Strengthening the magnitude of atmospheric cloud longwave heating rate makes the ITCZ more concentrated in the control simulation, and results in a more positive shortwave low-cloud feedback in +4K experiments.

Further analysis of these experiments suggests the following mechanism. A more concentrated and intense ITCZ results in stronger subsidence and warmer temperatures in the subtropical lower free troposphere at the 700 hPa level. This strengthens the trade inversion, resulting in more subtropical low-level cloud in the present day climate. Having more low-level cloud in the control climate amplifies the magnitude of the positive subtropical cloud feedback under climate change.

We argue that this is a credible physical mechanism which may explain the relationship between the simulation of the ITCZ and the climate sensitivity. This provides further support for the climate sensitivity being towards the upper end of the inter-model range.

**Afternoon Session: Topic IV / 92**

## A model for the relationship between humidity, instability and precipitation in the tropics

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According to the convective quasi-equilibrium paradigm, moist convection may be viewed as acting to rapidly remove conditional instability that is produced by large-scale uplift or radiative processes. Indeed, the convective mass flux within climate models is often parameterised to be directly dependent on measures of conditional instability such as the convective available potential energy (CAPE). Observationally, however, tropical precipitation has only a weak relationship to instability, and it is instead highly correlated with the environmental humidity. For instance, recent observational analyses have revealed that while CAPE peaks when the free troposphere is relatively dry, the highest daily precipitation rates are observed in regions where the free troposphere is close to saturation.

Here, we seek to untangle the physical mechanisms that lead to the observed relationships between convection, humidity and instability in the tropics. We construct a simple bulk-plume model for an ensemble of convective clouds under the influence of large-scale moisture convergence, extending the work of Romps (2014) who examined the special case of radiative-convective equilibrium. According to this model, both high precipitation and high humidity are caused by large-scale convergence within the atmosphere, even in the absence of any direct sensitivity of convection to environmental moisture. Furthermore, the plume model predicts that CAPE is maximised for weak convergence, when the tropospheric humidity is low. These relationships are reproduced in a set of simulations with a cloud-resolving model run to equilibrium with imposed large-scale vertical velocity profiles.

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## Meeting of HD(CP)<sup>2</sup> steering committee

**Morning session: Topic IV / 34**

### Convective aggregation, clouds, and climate sensitivity in RCE simulations

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RCEMIP, an intercomparison of multiple types of models configured in radiative-convective equilibrium (RCE), has recently been organized. Here, we describe the scientific objectives of RCEMIP and present preliminary results. First, clouds and climate sensitivity will be investigated in the RCE setting. This includes determining how cloud fraction changes with warming (a large source



of uncertainty in estimates of climate sensitivity) and the role of self-aggregation of convection (which has potentially large but unknown implications for climate sensitivity). Second, RCEMIP will quantify the dependence of the degree of convective aggregation on temperature. Finally, by providing a common baseline, RCEMIP will allow the robustness of the RCE state, cloud feedbacks, and convective aggregation across the spectrum of models to be assessed. A novel aspect and major advantage of RCEMIP is the accessibility of the RCE framework to a variety of models, including cloud-resolving models, general circulation models, global cloud-resolving models, and single column models.

**Morning session: Topic IV / 302**

## **On the importance of the surface flux formulation in large-eddy simulations of radiative-convective equilibrium**

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Convective self-aggregation is often observed in simulation studies of Radiative-Convective Equilibrium (RCE). Its spontaneous occurrence, despite spatially homogeneous initial conditions and forcings, remains elusive, mainly due to its high sensitivity to many aspects of the model setup (Wing et al, 2017). In an effort to better understand this problem, RCEMIP (RCE Model Intercomparison Project) has been organized (Wing et al., 2018).

The surface flux feedback is one of the mechanisms that is suggested to promote self-aggregation. The enhanced surface winds in convectively active regions enhance the latent heat fluxes, leading to a further moistening of those regions. These effects are suggested to outcompete the reduction in latent heat fluxes due to the fall in moisture gradient between surface and atmosphere in moist regions.

The importance of the surface flux feedback in self-aggregation in RCE opens up the question how important the surface flux formulation is in simulations of RCE. Interestingly, under conditions of free convection, such as those of the RCEMIP case, most surface-flux formulations run into problems. This is because the Monin-Obukhov Similarity Theory on which they are built breaks down in the absence of gradients in the mean wind speed. Therefore, many models put a lower bound on wind speed in the computation of the fluxes. We hypothesize that this artificial enhancement can interfere with the surface flux feedback, because in the calm dry regions, surface fluxes can be artificially enhanced.

We have set up an LES experiment based on a small-domain version (150 km x 150 km) of the RCEMIP case in which we compare the simulated RCE state of two simulations: one with a minimum wind speed of 0.1 m/s in the formulation of the surface fluxes, and one with a minimum of 1 m/s, as suggested by the RCEMIP description. Preliminary results of the former show that for the first 12 days, the fraction of the domain below 1 m/s exceeds 80% of the total surface area. Moreover, the average wind at the lowest level in the domain has mostly been well below 1 m/s, only reaching 0.8 m/s after 11 to 12 days. In the latter experiment, the minimum wind speed of 1 m/s leads to an increase in latent heat flux that can exceed that of the former case up to 60%, resulting in a stronger, but spatially more homogeneous convection.

**Morning session: Topic IV / 135**

## **Clouds and Convection in RCEMIP Simulations with the Community Atmosphere Model**

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The Radiative-Convective Equilibrium Model Intercomparison Project (RCEMIP) is an intercomparison of multiple types of numerical models, including atmospheric general circulation models (AGCMs), configured in radiative-convective equilibrium (RCE). This work presents the preliminary results of the RCEMIP simulations using the Community Atmosphere Model (CAM) AGCM performed with two different physics parameterizations packages, versions 5 and 6. These simulations are used to explore how cloud fraction, cloud feedbacks and convective aggregation changes with surface warming, and how consistent these results are across varying CAM physics parameterizations. This work is an important first step in the scope of the larger intercomparison framework to explore the robustness of cloud processes related to climate sensitivity across a hierarchy of numerical models, including cloud-resolving models (both limited-area and global), single column models and AGCMs (e.g., CAM).

**Morning session: Topic IV / 131**

## **Convective Self Aggregation and Radiative Convective Equilibrium across the MPI-M model hierarchy**

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Simulations of radiative convective equilibrium (RCE) have greatly influenced the understanding of climate, and climate change. Early simulations were performed with very simple one-dimensional models of the atmosphere, followed by cloud-resolving simulations. In the last five years it has also become common practice to simulate RCE with comprehensive general circulation models.

These recent studies revealed that different RCE states can be found, depending on how convection aggregates, even in the absence of external asymmetries in the forcing, and have motivated the RCEMIP project, which defines a standardized experimental protocol, to study RCE across a range of models. Here we present findings from our investigation of simulations performed – with the full spectrum of models developed and applied at the Max Planck Institute for Meteorology – as a contribution to RCEMIP and the World Climate Research Programmes Grand Challenge on Clouds Circulation and Climate Sensitivity. Our analysis emphasizes how commonalities (or differences) are manifest in the base RCE state, how this base RCE state depends on convective aggregation, how convection self-aggregates, and how these properties respond to warming. Simulations are performed using the UCLA-LES and ICON-LEM models (which resolve shallow clouds but with different microphysics), the cloud-resolving configuration of the ICON-NWP model, along with ECHAM and ICON-A, the atmosphere components of the MPI-ESM and ICON-ESM, respectively. The simulations and their differences are interpreted with the help of KONRAD, a simple one-dimensional model with a relaxed convective adjustment scheme and a simple prescription of cloud properties.

**Morning session: Topic IV / 173**

## **The spatial distribution of deep convection in a self-aggregation study**

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It is now well-known that, under homogeneous external forcing, convection can self-aggregate. The self-aggregation process is marked by a transition from a random state to a clustered state, often characterized by one circular convective cluster. Investigating the spatial distribution of convection within that cluster we find that convection is regularly intensified at its edge. The reason for this edge intensification is not because the edge is thermodynamically more favorable, as, in fact, convective available potential energy, convective inhibition and free tropospheric humidity are almost homogeneous within that region, but because it is marked by surface fluxes and strong surface convergence. We show that the enhanced surface convergence results from the convergence between convectively induced cold pools and a strong low-level inflow caused by a radiatively driven shallow circulation. In fact, as we show, the entire convectively active region is made up of individual cold pools whose collective effects can be treated as a single “super-cold pool”. By estimating the potential propagation speed of the super-cold pool boundary we show that it matches the speed of the inflow velocity and in that way controls the location of convection and the size of the cluster. Finally, comparing the spatial distribution of convection in the self-aggregation study with current high-resolution simulations over the tropical Atlantic we show that it is reminiscent to the intensification of convection that has been noted at the edge of the Intertropical Convergence Zone.

**Morning session: Topic IV / 167**

## How important is convective organization?

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The organization of convection on a wide range of scales is a well-known and particularly striking feature of satellite imagery. But are these features more than candy for the eye? Here we investigate two potential effects of convective organization. The first hypothesis is that convective organization may be controlling the precipitation amounts in the ITCZ, in particular leading to stronger precipitation. To test this hypothesis we investigate the relationship between spatial convective organization and precipitation in the tropical belt using global convection-permitting simulations that were conducted at a grid spacing of 2.5 km. The precipitation field is segmented into objects and relationships between area of objects, number of objects, precipitation and organization indexes are investigated. Against our initial hypothesis we find that convective organization and precipitation are independent to each other. If anything increasing precipitation requires decreasing organization. As a second potential effect of convective organization and given the limited effect of convective organization on the rain amounts in the the tropical belt, we investigate whether convective organization may rather be important for climate by controlling the mean state of the subtropics. Our second hypothesis is that more aggregated ITCZ states lead to drier and more extended subtropics. Such a relationship was suggested in radiative convective equilibrium simulations; we probe it here using realistically-configured simulations and observations.

**Morning session: Topic IV / 225**

## Microphysical Impacts and Large-Scale Wind Influences on Tropical Convective Organization in RCE

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Radiative-convective equilibrium (RCE) is an often-used paradigm in which to study processes in tropical oceanic convection. Two RCE topics that have remained relatively unexplored to date, particularly in large-domain channel RCE simulations that permit organized convection, are (a) the effect of background winds and (b) the influence of microphysical assumptions. The goal of this research is therefore to assess the impact of varying strengths of initial background winds and the microphysical scheme complexity (one- and two-moments) on the RCE state and the embedded convective system characteristics. In order to accomplish this goal, large channel 3D RCE simulations at 1 km horizontal grid spacing have been conducted with initial horizontally and vertically homogeneous wind speeds of 0, 2, 5, and 10 m/s, and using both one- and two-moment microphysics schemes, for a total of eight simulations. Initial results suggest that although the wind speed influences the midlevel humidity, the bulk RCE statistics are more strongly influenced by the microphysics scheme complexity than by the initial wind speeds. Both the winds and the microphysical assumptions have strong controls on the structure and propagation of the moist bands, as well as on the propagation and intensity of the embedded convective systems, highlighting the complexity of microphysics-dynamics interactions within the RCE states. Processes responsible for the demonstrated sensitivities in the convective system properties, particularly the coupling between the convective systems, their associated cold pools, and large-scale waves within the simulations, will be assessed and presented.

**Morning session: Topic IV / 301**

## Mesoscale variability of LES based superparameterized subtropical marine shallow cumulus convection

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The Dutch Atmospheric Large Eddy Simulation (DALES) is used as a superparameterization in ECMWF's OpenIFS global model to explore the representation of mesoscale variability of subtropical shallow cumulus convection over the Atlantic Ocean near Barbados. By enabling this superparameterization only over a designated area it is possible to use high-resolution local (DALES) model instances covering the full horizontal extent of the corresponding global model's columns.

This way the LES based superparameterizations can be viewed as a realistic benchmark for parameterized representation of clouds, convection and turbulence. Potential shortcomings of this approach are likely attributable to the scale break introduced by the coupling between the superparameterized processes and the resolved dynamics of the global model.

Analyses shows that the superparameterized clouds and their liquid water content are systematically underestimated creating a "cloud fraction hole" in the global model with only unorganized shallow cumulus convection in the superparameterized region. This lack of clouds is likely related to an underestimation of the humidity variability in the local (DALES) model instances. The "cloud fraction hole" disappears and organised cloud structures appear if sufficient humidity variability as dictated by the global model is added to the local model instances.

These results points in the direction that the exchange of variability between resolved and (super)parameterized scales is a potentially missing mechanism for the representation of clouds, convection and their organization.

**Morning session: Topic IV / 196**

## Exploring the aerosol-cloud-radiation relationships in deep marine stratocumulus layers

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Marine stratocumuli cover around a fifth of the world's oceans and are a key contributor to Earth's radiative balance at the surface (Wood et al. 2012). Their sensitivity to changes in anthropogenic aerosol concentrations remain a key uncertainty in the climate system. Our current understanding of their sensitivity and the plausible range of the aerosol-cloud radiative forcing is largely based on the process understanding obtained from field campaigns, high-resolution modelling, and satellite records of aerosol-induced phenomena such as volcano or ship tracks.

Yet, a large fraction of these records is only applicable to relatively shallow planetary boundary layers (PBLs). Ship tracks are only found in boundary layers up to a depth of 800 m. Field campaigns and high-resolution modelling studies of aerosol-cloud-radiation interactions in marine stratocumuli have been restricted to a similar range of PBL depths in the past. Meanwhile over 70% of marine boundary layers reside in deeper PBLs (Mühlbauer et al. 2014). Deep boundary layers tend to be decoupled more often than shallow layers, are associated with stronger cloud-base precipitation rates, and larger spatial scales of cellular organisation than shallow layers. All of these factors may influence aerosol-cloud-precipitation and aerosol-cloud-radiation interactions. Previous simulations of deep open-cell stratocumuli have shown that although ship tracks are not detected in deep PBLs, the induced change in cloud-radiative properties may be comparable and may not be predominantly associated with the Twomey effect, but rather changes in detrained cloud amount and cloud fraction (Possner et al. 2018).

Here, we combine a range of datasets to investigate the relationship of cloud-radiative properties for different boundary layer depths and aerosol concentrations. Cloud-radiative properties are obtained from the SYN1deg dataset (Doelling et al. 2013) and are put in relation with PBL depth (Eastman et al. 2016). Estimates for droplet number (Nd) are inferred from MERRA 2 boundary layer sulphate concentration (McCoy et al. 2017).

Our initial analysis suggests that moderately polluted ( $N_d < 100 \text{ cm}^{-3}$ ) clouds in deeper than 2.5 km PBLs are associated with 18% higher all-sky albedo, 5% lower effective radii, and 6% higher liquid water paths as compared to moderately polluted shallow clouds (PBL depth below 1km). In further analysis the susceptibilities of different cloud-radiative properties for different PBL depth regimes will be compared.

**Morning session: Topic IV / 232**

## The two faces of precipitation suppression by aerosol

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One of the mechanisms by which anthropogenic aerosols force the global climate is by suppressing precipitation in warm clouds. Uncertainty on this component of the aerosol–cloud interaction constitutes a sizable fraction of the total uncertainty on the aerosol forcing. In GCMs, precipitation suppression by aerosol results from parameterized processes, making it desirable to impose observational constraints to increase the physical realism of the model. We show that, in ECHAM6-HAM2, it is possible to formulate observational constraints on the modeled precipitation suppression using process-sensitive satellite observations of warm rain. Constraints on drizzle indicate an underestimate of the radiative forcing adjustment in the model, whereas constraints on more intense rain indicate an overestimate. Using DYAMOND to estimate the variability of warm rain processes within a GCM grid box is one way to break the degeneracy between the drizzle- and rain-based constraints.

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## Walk around Campus

Poster Session C / 41

### Feedbacks of mesoscale convective systems with circulation and radiation

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Mesoscale-organized convection brings the majority of precipitation in certain tropical regions and can further develop into cyclones with sufficient tropospheric humidity and vorticity. These convective systems are not yet represented in global climate models, given their intermediate scale and complex dynamics. For estimates of the precipitation associated with these systems throughout the tropics, we collocate ISCCP deep convective tracking data with rain rate measurements from the Multi-Source Weighted-Ensemble Precipitation (MSWEP) dataset. We also construct climatologies of the collocated anvil properties using the LMD-AIRS upper tropospheric cloud (UTC) database and look at the variation of both precipitation and anvil structure with sea surface temperature anomalies. To more thoroughly understand the feedback of these mesoscale systems with circulation, we construct vertical profiles of their horizontal and vertical winds, divergence, and condensate mixing ratios with ERA-Interim reanalysis values. These links between organized convection, meteorological conditions, and precipitation can be used to inform parameterizations of mesoscale convection going forward.

Poster Session C / 63

### How sensitive are the ICON-LEM simulations to microphysical assumptions?

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The microphysical properties of convectively generated ice clouds are investigated. Understanding ice clouds is crucial due to their importance for the radiation budget of the atmosphere. Ice clouds are in a large part determined by the dynamical context, ranging from cirrus formed in situ in ice-supersaturated regions connected with slowly ascending motion and mesoscale gravity waves, to thick anvil cirrus and stratiform cloud originating from deep convective outflow and large scale features with embedded convection.

We performed sensitivity studies with ICON on a horizontal resolution of 624m. The simulations are conducted for the 5th of July, 2015, which is a day with strong convection around 16UTC in the afternoon in the western part of Germany with subsequent precipitation. The two-moment microphysical scheme of ICON was adapted to different assumptions for the properties of cloud ice and snow. Beyond that, the influence of the used cloud condensation nuclei and ice nuclei scheme on the results was analyzed. A large effect on the ice water content was found due to changes in the ice particle geometry. In this experiments the cloud ice is specified as hexagonal plates or dendrites with a lower terminal fall velocity compared to the cloud ice of the control run and additionally with D2 geometry for the dendrite case. Using a sticking efficiency of  $\exp(0.025x)$  instead of  $\exp(0.09x)$  which was used in the control run increases the sticking efficiency significantly and shows a strong response in the results as well. Additionally the simulation results are compared to observations to identify the best match between model and observation and help to improve the microphysical parametrization in the model.

**Poster Session C / 259**

## **Heterogeneous ice formation in ICON-LEM in relation to statistics from ground-based remote-sensing observations**

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The occurrence of the ice phase in clouds and precipitation is crucial for the determination of precipitation characteristics, the thermodynamic structure of the atmosphere and radiative transfer. In particular, the heterogeneous formation of ice at temperatures between 0 and -40°C still requires a thorough characterization. The formation of ice crystals in this temperature regime is not only dependent on temperature and amount and phase of available water, but also on the availability of ice nucleating particles (INP) which are only a small fraction of the whole reservoir of aerosol particles. For the subsequent evolution of the ice crystals towards precipitation hydrometeors, secondary ice formation processes and ice multiplication processes play an essential role. Nevertheless, their interplay is to date not fully understood.

State of the art numerical models like the ICON-LEM, which was utilized within the German research initiative High-Definition Clouds and Precipitation for advancing Climate Prediction (HD(CP)<sup>2</sup>), relies on parameterizations to account for pristine ice formation and the ice multiplication processes.

It is a unique feature of these ICON-LEM simulations, that they cover the huge area of whole Germany with a spatio-temporal resolution reaching down to 156 m in the order of seconds. This enables to evaluate the model with techniques which were previously only available for spatio-temporally high resolved remote sensing measurements such as done within Cloudnet (Illingworth et al., 2007).

Within the presented study, we used the 1-d meteogram (time-height) output of ICON-LEM to apply a mixed-phase cloud characterization algorithm of Bühl et al. (2016) to investigate ice formation in ICON-LEM. We evaluated the results with those obtained from a long-term remote-sensing dataset of the Leipzig Aerosol and Cloud Remote Observations System (LACROS) of Leipzig Institute for Tropospheric Research (TROPOS). The scales of the evaluation are 60 m in the vertical and 10 s in

time. Also direct comparisons for several runs of ICON-LEM are available for the German Cloud-net sites. A selection will be presented. Evaluated parameters comprise ice water content, liquid water content, cloud layer depth. The availability of the ICON-LEM output also opens new ways for the interpretation of the remote-sensing observations, because the simulations provide the ice and liquid water content and number concentrations separately for different hydrometeor types (Seifert and Beheng, 2006) which is to date hardly possible to be obtained from the remote-sensing observations.

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**Poster Session C / 47**

## **A wavelet based analysis of convective organization in ICON large-eddy simulations**

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Wavelet spectra of rain rates are used to characterize convective organization in high-resolution simulations (horizontal grid spacing 156 m) with the large-eddy model ICON-LEM over Germany. Scattered convection takes place on scales between 1.2 and 4.8 km, while organized structures like supercells or mesoscale convective systems act on scales above 4.8 km. Organization of convection within squall lines is visible in the spectra as spectral energy is increased in certain directions. We further investigate the dynamical properties that relate to convective organization, and highlight the role of parameters such as CAPE and wind shear.

Preferred spatial scale, average convective rain rate and anisotropy as inferred from the wavelet spectra are important characteristics to quantify convective organization. They are used to introduce a wavelet based organization index (WOI). With regard to other indexes for convective organization, WOI does not require the definition of objects. Using the WOI we are able to differentiate organized from non-organized convection.

Furthermore it is possible to define a local wavelet based organization index (LWOI) to determine regions with different degrees of convective organization, i.e. in ICON-LEM simulations or Tropical Rainfall Measuring Mission (TRMM) observations over the Tropical Atlantic.

**Poster Session C / 51**

## **Scale interactions and anisotropy of turbulence in stable boundary layers**

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Stable boundary layer turbulence represents a challenge for numerical weather prediction due to its intermittency and unsteadiness caused by the interactions of processes on multiple scales. In weak-wind conditions, sporadic turbulence can be triggered by sub-mesoscale motions which are poorly understood and mainly not represented in models. In addition, the Reynolds stress tensor in these conditions is highly anisotropic which leads to the failure of traditional similarity scaling relationships used to parameterise the turbulence.

Recently developed methods of nonstationary data analysis represent a promising tool to extract knowledge about turbulence triggering mechanisms from observational datasets of atmospheric turbulence. We analyse the nonstationary response of turbulent vertical velocity variance to non-turbulent, sub-mesoscale wind velocity variability using the bounded variation, finite element, vector autoregressive factor models (FEM-BV-VARX) clustering method, based on the FLOSSII dataset of nocturnal near-surface turbulence. Several locally stationary flow regimes are identified in which the influence of sub-mesoscale wind velocity on the turbulent vertical velocity variance differ. In each flow regime, we analyse multiple scale interactions and quantify the amount of turbulent variability which can be statistically explained by the individual forcing variables. Our analyses show that the state of anisotropy of the Reynolds stress tensor in the different flow regimes relates to these different signatures of scale interactions. In flow regimes dominated by sub-mesoscale wind variability, the Reynolds stresses show a clear preference for strongly anisotropic, one-component axisymmetric stresses, which tend to correspond to periods in which the turbulent fluxes are against the mean gradient. These periods additionally show stronger persistency in their dynamics, compared to periods of more isotropic stresses. Turbulence parameterisations in strongly stable conditions would greatly benefit from attributing scaling relationships depending on the turbulence topology, and our analysis gives insights on how the different topologies relates to nonstationary turbulence triggering by sub-mesoscale motions.

**Poster Session C / 247**

## Effects of aerosol on shallow cumulus cloud fields

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The study of shallow convection is generally limited by the need to balance higher resolution, and larger domain sizes; capturing in more detail the small scale cloud processes on the one hand, and the behaviour of the entire cloud field on the other. In this work we hope to go some way towards addressing this by carrying out cloud resolving simulations on large domains. Simulations of trade wind cumulus are carried out using the Met Office Unified Model (UM), based on a case study from the Rain In Cumulus over the Ocean (RICO) field campaign. The UM is run with a nested domain of 500km with 500m resolution, in order to capture the large scale behaviour of the cloud field, and with a double-moment interactive microphysics scheme. Simulations are run using aerosol profiles based on observations from RICO, which are then perturbed. We find that the aerosol perturbations result in changes to the convective behaviour of the cloud field, with higher aerosol leading to an increase (decrease) in the number of deeper (shallower) clouds. However, despite this deepening, there is little increase in the frequency of higher rain rates. This is in contrast to more idealised studies which have found greater aerosol loading drives pronounced increases in stronger precipitation from deeper clouds, ultimately leading to similar final states of the cloud field. Coupled with suppressed onset of precipitation, we find that increasing aerosol results in

a persistent increase and decrease in domain mean liquid water path and precipitation, respectively, with little impact on cloud fraction.

Poster Session C / 277

## A new lidar technique for observation of high-resolved profiles of droplet effective size and number concentration in liquid-phase clouds

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A novel lidar polarization method for the retrieval of microphysical properties of liquid water clouds was developed and implemented at Leibniz Institute for Tropospheric Research (TROPOS). The technique makes use of measurements of the linear depolarization ratio with a dual-field-of-view (DFOV) lidar system. The inversion of the droplet effective size and number concentration is based on the relation between lidar multiple scattering, depolarization, and cloud microphysics. Besides the acquisition of temporally high resolved cloud microphysical retrievals (30 s), the lidar technique is in addition also capable to obtain profiles of the extinction coefficient of aerosol particles in the vicinity of the clouds. This permits to study aerosol-cloud interaction on scales from seconds to hours with a vertical resolution in the order of 30 m. By means of this conference contribution, the measurement principle and the results retrieved with the DFOV Polarization technique from observations obtained within one year at Leipzig, Germany, will be presented. Application of the statistics from these observations for the evaluation of the warm-cloud microphysics simulated by the ICON Large Eddy Model (ICON-LEM) will be shown.

The DFOV Polarization technique was in the meantime implemented also into other lidar systems of TROPOS. Only a minimal instrumental upgrade is required. Currently the technique is operational in three lidar systems for measurements at three locations of key relevance for atmospheric sciences: in the mostly anthropogenically polluted continental environment of Leipzig (51.3° N, 12.4° W, since 2016), in the mostly naturally polluted marine environment of the Atlantic Ocean (Shipborne: northern and southern hemisphere, November-December 2018) and the mostly pristine marine environment of Punta Arenas, Chile (53.1° S, 70.1° W, since November 2018, see the poster about the DACAPO-PESO field campaign). First preliminary results will be presented and insights of a dependency of the so-called aerosol cloud interaction index (ACI) to different environments will be discussed.

Poster Session C / 62

## Characterizing density currents in ICON-NARVAL simulations

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Convectively generated density currents (usually named “cold pools”) are well known fundamental features of precipitating convection. In the past decade, cold pools have been extensively studied in high resolution simulations over oceanic or land-like surfaces. However, most of these studies were done over small to intermediate simulation domains, and mostly in idealized frameworks. A

lot of different methodologies are actually proposed in the literature, but none of them have been yet applicable to very large scale simulations, including realistic surfaces and a synoptic weather systems.

Then, this work is the first attempt to define density currents from high resolution simulations outputs without any preliminary assumption concerning their horizontal length scale, as it is commonly done when using temperature spatial anomalies. Here, the goal is to build an objective method to detect density currents in a similar way over oceans as well as over lands, at any time of the day, even in the presence of a complex topography or any other surface heterogeneity. The overall objective is to better understand common aspects and distinct features of land versus oceanic convection.

Moire specifically, this study is also devoted to the analysis of the thermodynamical and dynamical properties of the density currents and their close environment. It is based on CRM (2.3 km resolution) simulations ("NARVAL" simulations, Daniel Klocke) centered over the Tropical Atlantic and performed with ICON model (MPI/DWD). The results show that, depending on the surface type, the wind shear, the cloud base height and the environmental moisture, the density currents have different shapes, propagation velocity, propagation direction (downwind or upwind) and are more or less subject to merge and generate squall lines.

Density currents also play an important role in organizing shallow and deep precipitating convection. Then, the detailed characterization of these particular objects, here proposed, offers the opportunity to better understand their role in organizing convection, not only in the ITCZ core, but also in the ITCZ edge. Indeed, a particular attention will be paid to the density currents generated by shallow precipitating cumulus during the EUREC4A observational campaign in the Barbados region (planned for January 2020).

In a middle term prospective, this work can also provide a deeper insight on convection internal dynamics - especially the cold pools mechanical efficiency in recycling convection through boundary layer lifting - which is of great interest for convective parameterizations development.

## Poster Session C / 112

# Precipitation over the Southern Ocean: Lessons from Macquarie Island

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Macquarie Island (54.5°S, 158.9°E) provides one of the few long-term meteorological records over the Southern Ocean (SO) with daily records of precipitation and surface temperature dating back to 1948. Hourly temperature and precipitation records are available from 1998. Adams (2009) details that the annual precipitation at Macquarie Island increased, on average, at a rate of ~72 mm/decade over the period 1970 (800 mm) to 2008 (1080 mm) with the greatest increase occurring during the winter season. 2016 (1272 mm) and 2017 (1284 mm) have been two wettest years on record, 40% greater than the 1961-1990 average (911 mm).

These standard meteorological observations are a core component of the recent field campaigns over the Australia/New Zealand sector of the SO. They have been supplemented for a two-year period (2016-2018) covering the SOCRATES field campaign with a deployment of instruments from the US Department of Energy Atmospheric Systems Research (ASR) program.

A more recent analysis of the historical hourly precipitation records (Wang et al. 2015) examined the frequency and intensity of the surface precipitation observations revealing that light precipitation ( $0.066 \leq P \leq 0.5$  mm h<sup>-1</sup>) occurs more commonly (29.7%) than heavy precipitation ( $P \geq 1.5$  mm h<sup>-1</sup>, 1.1%). Only 60% of the precipitation was attributed to frontal systems, considerably less than the 80-90% reported by Catto et al. (2012) when using ERA-I precipitation.

New research details a further analysis of the precipitation records when sorted by the synoptic meteorology (distance from fronts and mid-latitude cyclones), which finds that ERA-I overestimates precipitation in the immediate vicinity of fronts, particularly in the warm sector. This new analysis

suggests that a significant portion of the surface precipitation observed over Macquarie Island is generated between frontal passages. We speculate that this is most likely from shallow boundary layer clouds (open and closed mesoscale cellular convection.) A diurnal cycle is also evident in these precipitation records, particularly during the summer season, suggesting that cloud and precipitation products based on A-train observations may be biased if used to represent daily values. ERA-I has limited skill in producing this diurnal cycle. This research complements earlier research examining biases in the boundary layer characteristics over the SO, as observed at Macquarie Island.

#### Poster Session C / 118

### Linking cold pools to precipitation intensification

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Evaporative cooling from precipitation results in colder and denser air, a cold pool (CP), which can organize deep convective thunderstorms. The anomaly causes a circular propagation along the surface and forms a characteristic gust front with narrow lines of strong horizontal convergence which results in vertical acceleration. Hence, CPs drive the interaction between multiple convective storms and may impact the intensification of thunderstorms in the late afternoon for diurnal cycle numerical experiments. However, how they intensify or hamper convection is still not fully understood. A better understanding thereof requires an accurate determination of the spatial and temporal correlation between new convective events and the fronts of previous ones.

With a new tracking algorithm for CPs, we uncover the causal chain of sequential convection in shear-free large eddy simulations. Our algorithm identifies CP edges based on tracking particles that are advected by the spreading CP. The tracking of individual particles also reveals dynamics perpendicular to the direction of spreading. Accumulation of particles, containing the footprint of previous precipitation events, can be linked to subsequent convection and acts as a predictor for the location of precipitation.

Three types of interaction between CPs and convection are identified and characterized by the number of CP fronts contributing to a new event: convection triggered by a single CP, the collision of two CPs and the interaction between three or more CPs. Single fronts do sometimes trigger a new convective event. However, they often prevent the new event to intensify through cold air propagating further underneath the new event and decoupling it from mass and energy fluxes. The collision of two CP fronts builds up an intersection line with convection likely to occur near the two end points of this collision line. Finally, the interaction between three or more CPs reduces the degree of freedom in a way that air is inevitably forced upward. The geometric configuration, including the distance and speed of the CP fronts, determines how much air is captured between propagating cold pools. The amount of air captured, the moisture content of this air and the time to build up instability are proposed as predictors for the strength of subsequent convection.

#### Poster Session C / 303

### Tropical Clouds and Precipitation “Across Scales” in Convection-Permitting Aquaplanet Simulations

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Tropical clouds and precipitation are important components of Earth's climate system, yet our understanding about their coupling with dynamic systems across different spatiotemporal scales remains limited. An especially challenging issue is how the interplay between clouds, precipitation, and dynamics can result in conditions that favor intense rainfall over prolonged periods of time. As numerical weather prediction models move to higher and higher resolution, the question remains as to whether high-resolution global models will be able to accurately capture that interplay and the resulting extreme precipitation events. Those issues motivate this study, which aims at studying tropical clouds and precipitation in global, convection-permitting idealized model simulations.

A set of aquaplanet experiments were produced with the Model for Prediction Across Scales (MPAS) largely following the experimental design from the AquaPlanet Experiment. A refined mesh was utilized to allow convection-permitting resolution (3-km mesh spacing) in the tropics with 15-km mesh spacing elsewhere. This unique simulation captures a wide variety of phenomena ranging from tropical mesoscale systems to synoptic-scale warm conveyor belts to planetary-scale convectively-coupled equatorial waves. A long integration period, following model spinup, will be used to composite different phenomena and to determine the coupling between clouds and their circulations resulting in heavy-precipitation events. Results from that analysis will guide the refinement of hypothesis, observation strategies, and modeling techniques to be employed during a planned US-Taiwan-Japan field experiment about tropical precipitation in 2020.

#### Poster Session C / 186

### Perturbation of natural cirrus due to contrail ice nucleation

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Aircraft emissions are a large source of anthropogenic aerosols in the upper troposphere. Contrails form during the mixing of the hot exhaust plume with environmental air when supersaturation with respect to water is reached. Emitted soot particles first activate into water droplets and subsequently freeze and form contrail ice crystals. The nucleation rate is dependent on soot number emissions and the atmospheric state. After ice crystal formation most of the contrail ice crystals are trapped within downward propagating vortices and depending on the atmospheric conditions a fraction of ice crystals sublimate due to adiabatic heating of the air. Contrail formation in ice supersaturated regions increases cloudiness and contrail ice crystal formation within natural clouds affect the microphysical process rates and radiative properties of natural clouds.

We have implemented a contrail parameterization in the high resolution ICON-LEM to study the impact of contrail formation on cloud properties. We focus on the perturbation of natural cirrus due to contrail formation within cirrus and the interaction between natural cirrus and contrail ice crystals. We take into account the change in the survival fraction of contrail ice crystals due to the presence of natural cirrus ice crystals, which get entrained into the contrail plume during mixing and sublimate during the vortex descent increasing relative humidity locally in the vortex. We study the modification in natural cloud properties induced by contrail formation within clouds, the resulting changes in microphysical process rates and the life time of those cloud perturbations.

#### Poster Session C / 239

### Mixing and Cumulus Thermals

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Cumulus cloud mixing is a key process that has an impact on the onset, development, and decay of atmospheric convection. It is also relevant for the climate system, since it determines how clouds are impacted by and how they impact their environment and therefore the large scale. Using idealized Large Eddy Simulations of deep convection we investigate the role of mixing in the fate of individual cumulus thermal vortices. We find that (a) both initial conditions and entrainment history are important predictors for the “success” of individual thermals, and (b) that environmental moisture is more important as a source of internal moisture content for initiating thermals than via mixing as they rise. This has to do with the short lifetime, and in general the transient nature of individual cumulus thermals, a feature that might be important for new developments of convection parameterizations.

**Poster Session C / 213**

## **Bulk and structural convergence at convection-resolving scales in simulations of summertime moist convection over land**

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Convection-resolving models can successfully reproduce important physical processes related to moist convection without a convection parameterization. They are today established as a solid framework to simulate moist convection in regional-scale climate models. Moreover, recent studies have demonstrated that convection-resolving global climate simulations are feasible. However, capturing the different scales of the processes governing moist convection is challenging. Previous studies have shown that the size and properties of individual clouds and updrafts do not converge until horizontal grid spacings ( $\Delta x$ ) of  $O(100\text{ m})$ . We refer to this as structural convergence. On the other hand, a few recent studies have demonstrated that domain-averaged and integrated properties related to a large ensemble of convective cells converge at the kilometer scale. We refer to this as bulk convergence.

This study investigates both the bulk convergence of the mean diurnal cycle and spatial distribution of precipitation, clouds and convective transport, and structural convergence of cloud-scale statistics in real-case convection-resolving simulations. Two 9-day episodes of quasiperiodic diurnal moist convection are simulated at  $\Delta x = 8.8, 4.4, 2.2, 1.1\text{ km}$  and  $550\text{ m}$  over the Alps and over Central Germany to compare the results in the presence and in the absence of a pronounced orographic forcing. Results reveal that bulk convergence is systematically achieved in both episodes for the spatial distribution of the analyzed quantities. For their mean diurnal cycle, bulk convergence is generally observed in simulations over the Alps, but not over Central Germany, indicating that the presence of a mesoscale orographic forcing reduces the resolution sensitivity of the bulk flow properties. Structural convergence is confirmed to be not yet achieved at the kilometer scale. In particular, the size and strength of the simulated convective updrafts and the size of the smallest clouds are largely determined by  $\Delta x$ .

Overall our analysis supports the use of kilometer-scale resolutions in regional-scale and global convection-resolving simulations, despite the inability of these models to fully resolve the associated cloud field.

**Poster Session C / 220**

## **A groundwater and runoff formulation for weather and climate models**

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Soil moisture modifies the state of the atmosphere and thus plays a major role in the climate system. Its spatial distribution is strongly modulated by the underlying orography. Yet, the vertical transport of soil-water and especially the generation of groundwater runoff at the bottom of the soil column are currently treated in a crude way in most atmospheric and climate models. This potentially leads to large biases in near-surface temperatures during mid-latitude summertime conditions, when the soils may dry out. Here we present a modified formulation for groundwater runoff formation. It is based on Richards equation, allows for saturated aquifers, includes a slope-dependent groundwater discharge, and enables a subgrid-scale treatment of the underlying orography. The proposed numerical implementation ensures a physically consistent treatment of the water-fluxes in the soil column, using ideas from flux-corrected transport methodologies. An implementation of this formulation into TERRA\_ML, the land-surface model of the regional climate model COSMO-CLM, is validated both in idealized and real-case simulations. Idealized simulations demonstrate the important role of the lower boundary condition at the bottom of the soil column, display a physically meaningful recharge and discharge of the saturated zone, and exhibit a closed water budget. Validation against measurements at selected stations show an improved soil-water content. Finally, decade-long climate simulations over Europe exhibit a more realistic representation of the groundwater distribution across continental scales and mountainous areas, an improved annual cycle of surface latent heat fluxes, and as a consequence reductions of long-standing biases in near-surface temperatures in semi-arid regions. This is demonstrated both for simulations using a grid spacing of 50 km and kilometer-scale simulations.

**Poster Session C / 180**

## **EarthCARE potential of sensor-synergy between imager and atmospheric lidar to characterized cloud types with respect to the geometrical and radiative cloud top height**

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The CloudSat and CALIPSO together have shown that the past interpretation of cloud radiance with passive observations has changed in light of the new profile information.

The ESA's cloud and aerosol mission EarthCARE will provide measurements from active sounder and passive imager from one platform and make it possible to continue the interpretation of passive observation directly from track to swath. The active backscatter lidar (ATLID) will provide vertical profiles of cloud and aerosol parameters with high spatial resolution. The lidar instrument measures in nadir view, while the passive multi-spectral imager (MSI) has a swath of 150km and a pixel size of 500m. MSI observations will provide cloud products to extend spatial limited information of cloud properties obtained from the active sensors into the cross-track direction. Based on the stand alone retrievals we combine active and passive measurements to derive a synergetic cloud top height. The cloud top retrieval from MSI will be an infrared effective radiating height, which is located somewhere within the cloud. The ATLID cloud top height will give the physical boundaries of the clouds alongtrack which will be used to study the relationships between the effective and true cloud top height.

The analysis tool introduced by the International Satellite Cloud Climatology Project (ISCCP) are used to quantify the representation of cloud types according to their radiometric brightness temperatures (interpreted as cloud top height) and visible brightness (interpreted as optical thickness) as given from the passive instrument. This cloud type histogram is compared to the active measurements where now the cloud top height a geometrical cloud top height. The profile information can identify additional also the multi-layered cloud systems. These multilayered cloud system will be further investigated by using all MSI spectral information to get a better characterization on track to the entire swath. We have used MODIS and Calipso observations as a test bed and synthetic observations generated with the EarthCARE Simulator (ECSIM).

**Poster Session C / 105****Improved representation of the shape parameter for single- and double-moment bulk microphysics schemes**

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In this work, a new closure for the shape parameter of gamma droplet size distributions (DSD) in bulk microphysics schemes is proposed. It was obtained from warm-phase bin-microphysics simulations of cloud-top, using in situ DSD measurements as a reference. The new closure improved the representation of the DSD evolution, cloud droplet effective diameter and rain mixing ratio, in warm-phase 1D bulk microphysics simulations. It was also tested in a WRF 3D cloud-resolving framework, and compared to dual-polarization radar measurements and hydrometeor classification. The strongest effect detected is a reduction of cloud-top reflectivity due to a decrease in the amount of graupel, which increases the coherence between model outputs and radar observations.

**Poster Session C / 90****A multi-modal diagnostic cloud fraction scheme and its impact on cloud in convection-permitting simulations over the US Southern Great Plains**

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Cloud fraction parametrizations (CFPs) are indispensable in global atmospheric models to account for the effect of sub-grid clouds on radiation and precipitation microphysics. It is unknown up to what resolution such CFPs have added value compared with an all-or-nothing approach. This study has two objectives: (1) Demonstrate the benefit of CFPs for convection-permitting simulations (order 1 km grid length) and (2) Describe and evaluate a new approach for diagnostic CFPs.

Using synergistic lidar and radar ground-based remote sensing and satellite observations for a range of case studies over the US Southern Great Plains, it is shown that convection-permitting simulations without a CFP underestimate cloud cover and liquid water paths and overestimate the surface short-wave radiation.

Using a CFP with an underlying symmetric, uni-modal temperature and moisture distribution only alleviates these biases when operational bias correction techniques are applied.

A new diagnostic cloud fraction scheme is proposed that draws information from adjacent model layers, within reach of a turbulent mixing length. Combined with variances diagnosed in the boundary layer scheme, a multi-modal, skewed temperature and moisture distribution is reconstructed. The scheme closely reproduces the often observed behaviour of negative and positive moisture skewness below and above the boundary layer top respectively.

It is shown that the performance of the multi-modal cloud scheme is similar to the operational bias-corrected scheme in terms of cloud cover and surface radiation. It does so in a more physically meaningful and regime-dependent way, however. Moreover, the new cloud scheme outperforms the operational scheme in terms of the cloud water paths. Some of the ideas presented here are applicable to prognostic cloud fraction parametrizations as well, which will be the scope of future research.



## Poster Session C / 137

**Implications of “FAT” on the structure, microphysics, and precipitating characteristics of tropical deep convective clouds**Hassan Beydoun<sup>1</sup> ; Corinna Hoose<sup>1</sup><sup>1</sup> *Karlsruhe Institute of Technology***Corresponding Author(s):** hassan.beydoun@kit.edu

Variable SST radiative-convective equilibrium (RCE) simulations with ICON-LEM strictly follow the fixed anvil temperature (FAT) hypothesis (Hartmann and Larson, 2002), where radiative cooling atop high level clouds occurs at the same temperature independent of SST. We find that this constraint fixes the temperature of the entire high level cloud profile, which would imply that, in temperature space, tropical deep convective clouds (DCCs) expand from below.

We analyze the microphysical repercussions of this behavior and find that with warming condensation rates remain, on average, fixed for a given temperature. Therefore, the mechanism by which DCCs increase their precipitation is via condensing cloud water over a longer column. The unchanged condensation rate happens despite the weakening of large scale ascent implying that individual DCCs become more intense with warming and are accompanied by stronger evaporatively driven downdrafts. This is further corroborated by the fact that the precipitating efficiency – defined as the precipitation rate over the column integrated condensation rate – decreases from 45% to 27% over the SST range of 297 K to 310 K.

We apply a novel rain partitioning scheme within the microphysics parameterization which quantifies the contributions of cold and warm rain processes to the total rain budget. As expected, the warm rain contribution increases with warming, a direct result of the warmer cloud base in the higher SST simulations. The transition to warm rain dominant precipitation decreases mean rain drop size which contributes to stronger penetrative downdrafts and cold pools. This explains both the decreased precipitating efficiency as well as the strengthening of the intensity of individual DCCs. We therefore hypothesize a cold pool induced pathway by which precipitation become more intense with warming.

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## Poster Session C / 97

**Introducing a simple stochastic model to account for turbulent intermittency in subgrid-scale processes of storm-resolved models**Metodija M. Shapkalijevski<sup>1</sup> ; Nikki Vercauteren<sup>1</sup><sup>1</sup> *Freie Universität Berlin, Department of mathematics and computer sciences, Berlin, Germany***Corresponding Author(s):** m.shapkalijevski@fu-berlin.de

The predictability of atmospheric weather prediction and climate models depends on their limited resolution, which is induced by the discretization of the numerical scheme. This implies that subgrid-scale processes are not resolved, but parameterized. It has been shown that the parametrization of near-surface and boundary-layer turbulent transport processes are usual and important reasons of model error. The importance of an improved turbulence parameterization is even more dramatic in nocturnal and strongly-stratified flow, in which the scales of motion are smaller by an order or two magnitudes, compared to daytime and more turbulent (convective) flow. One of the difficulties in parameterization nocturnal (stable) boundary-layer turbulence is its intermittent character, and its random distribution in time and space. In this study an easy-to apply stochastic model that approximates and includes the effects of turbulence intermittency in atmospheric boundary-layer

turbulence parameterizations is introduced. The model treats the turbulent intermittency as random stochastic forcing on background turbulent flow. Consequently, the model approximates the intermittent events as continuous function of their probability density distribution. To find the required intermittent properties in a turbulent flow (frequency of occurrence, duration, and magnitude of intermittent events), we have used a turbulent event detection (TED) method applied on time series of high-resolution measurement data. By constructing and running a simple one-dimensional prognostic model of the horizontal wind velocity and potential temperature, and adding the stochastic model for turbulence intermittence in the turbulent kinetic energy (TKE) closure, we have tried to demonstrate the applicability, ability, and the relevance of this model to introduce intermittency in the turbulence parameterization in atmospheric numerical models (e.g. IFS, ICON, COSMO).

Poster Session C / 192

## ParaCon at Reading: New approaches for modelling convection

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Work at Reading University within the UK-wide ParaCon project seeks to develop new approaches to represent convective processes in models with resolutions spanning the “grey zone”. Here we present an overview of these activities, which include developing scale aware mass flux schemes, improved 3D turbulence parametrisations, and conditionally averaged fluid partitions. Process models run at LES resolutions are analysed to guide these developments, and future work is outlined.

Poster Session C / 262

## Deriving mixed-phase cloud properties from Doppler spectra of the millimeter-wave cloud radar

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Millimeter-wave cloud radars have become an effective tool in probing the microphysical parameters of clouds. At present, it has become a trend to analyze the evolution of microphysics using radar Doppler velocity spectrum. For conventional radar observations, the moments of the Doppler spectrum are computed and stored while the full Doppler spectrum is discarded. Therefore, radar-based cloud retrievals most often use only the spectral moment parameters. However, the particle size distribution and fall speed of different types of particles are large different in radar effective exposure volume, thus producing a bimodal or multimodal spectral signature. When using only the moments of the Doppler spectrum, important spectral information can be “smooth”. It has certain influence on the subsequent inversion of cloud microphysics parameters. In this paper, the zero crossing method is adopted to the derivation of effective signal above the noise level, looking for peak signal, and then

the local spectral is fitted with gaussian function to separate the Doppler spectra of different types of particles in the total spectrum. The results are as follows: (1) The bimodal spectrum of Doppler velocity can be used to retrieve the supercooled water content and the ice water content; (2) The radar reflectivity factor of mixed-phase clouds mainly depends on ice crystals. Therefore, it is considered that the effective volume of radar is ice crystals. The cloud liquid water content will be underestimated according to the reflectivity factor.

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## Ice crystal number concentration retrievals from satellite observations

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The number concentration of cloud particles is a key quantity to understand aerosol-cloud interactions and describe clouds in climate and numerical weather prediction models. In contrast with recent advances for liquid clouds, few observational constraints exist on the ice crystal number concentration (Ni).

This work presents results based on a newly developed retrieval of Ni - DARDAR-Nice - derived from combined lidar-radar measurements. Such instrumental synergy shows great strength to provide vertical profiles of Ni for numerous types of ice clouds. DARDAR-Nice has been thoroughly evaluated against in situ measurements from mid-latitude and airborne campaign, as well as in the context of case studies. This new product also appears consistent with theoretical expectations, despite clear limitations for mixed-phase clouds. Finally, global distributions of Ni were obtained and analyzed in order to reach a better understanding of the physical processes that control this parameter. Notably, a strong dependence was observed between Ni, the vertical velocity and, to a lesser extent, the temperature.

Further work concerns the use of this new satellite product, together with global reanalyses, to assess the importance of aerosol - ice cloud interactions. Despite numerous, and sometimes divergent, modeling results, very little has currently been done to understand these interactions on a global scale from satellite observations. Clear signals from such interactions are here noted and are exploited in view of presenting a first observational estimate of the aerosol - ice cloud radiative forcing.

Poster Session C / 171

## Trade wind cloud features from airborne and ground-based observations - two times the same answer?

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Two aircraft campaigns with the HALO (High Altitude Long range research aircraft) aircraft took place in the recent past in the vicinity of Barbados: NARVAL-South (Next-generation Aircraft Remote-Sensing for VALidation studies) in December 2013, during the dry season, and NARVAL2 in August 2016, during the wet season. During these two campaigns, a wide range of cloud regimes were sampled over the tropical Atlantic upstream of Barbados.

Since 2010, the Barbados Cloud Observatory (BCO) has been located on the east coast of the island of Barbados, where it is exposed to the undisturbed easterly trade winds. Two similar 35 GHz cloud radars are deployed on both, the BCO site and as part of the NARVAL payload. These cloud radar measurements are used to segment individual clouds entities for the ground-based measurements and the airborne data set. Overall, 6,411 clouds were segmented from airborne measurements and 79,469 from BCO observations. From these segmented individual clouds, macrophysical parameters are derived to characterize each individual cloud.

This presentation will relate the two aircraft campaigns upstream of Barbados to the long-term measurements at BCO, as the aircraft campaigns only sample a short snapshot of cloud regimes in comparison to measurements at BCO. One open question is how well the observations during the aircraft campaigns reflect the situation observed at BCO. Therefore, statistics of cloud macrophysical parameters from both, airborne observations and ground based measurements, will be analyzed for the two different seasons observed also by aircraft. Results show that during December, a broader range of cloud top heights from shallow convection is observed from the aircraft than at BCO. During August, ground-based observations show almost no high clouds, with cloud top heights above 8 km, while about 15% of the clouds observed by aircraft are high clouds.

**Poster Session C / 299**

## **Large-Eddy Simulation of a Stratocumulus-Topped Arctic Boundary Layer over Sea Ice**

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Arctic low-level stratocumulus is a main contributor to the intra-seasonal variability of the surface energy balance which in turn influences the existence and evolution of the clouds. Although stratocumuli may extend over hundreds of meters vertically, processes on scales below few tens of meters, such as cloud-top entrainment and mixing within the atmospheric boundary layer, drive their development. The interaction of radiation, microphysics, and turbulence represents not only a major challenge for climate and weather modelling but also for large-eddy simulation. Using highly-resolved large-eddy and direct-numerical simulation, recent studies (e. g. Matheou and Chung [2014], Kopec et al. [2016], and de Lozar and Mellado [2017]) for the first time provided a detailed view of the cloud-driving processes. Studies with comparable resolutions are non-existent for the Arctic where observational data is lacking, most clouds are mixed-phase, and the characteristic eddies are smaller.

We investigate low-level mixed-phase stratocumulus in Arctic summer over sea ice in a neutral boundary layer capped by a strong temperature inversion. Initializing and benchmarking our modified version of WRF-LES with data from the recent measurement campaigns ACLOUD and PASCAL [Wendisch et al., 2017] grants insight to the cloud-driving processes beyond what can be learned from observational data or large-eddy simulation alone. Based on the data from ACLOUD RF13 and corresponding measurements of PASCAL, we define a suitable LES scenario and perform a resolution-convergence study on it. This enables us to analyze cloud-driving non- or under-resolved microphysical, radiative, and turbulent processes and their interaction as well as the interaction of stratocumulus and the surface. We show for this case that the first-moments of e. g. liquid potential temperature, cloud water mixing ratio and boundary layer height are independent of the horizontal resolution only below 10m - less than what many other studies of low-level stratocumulus employ.

To ensure the sufficient representation of higher statistic moments and their effects, we apply an even finer resolution of 3.5m to our scenario.

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Kopec et al. (2016), *Q.J.R. Meteorol. Soc.*, vol142(701), 3222-3233.

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Wendisch et al. (2017), *EOS*, vol98(8), 22-26.

#### Poster Session C / 155

### The role of low-level clouds in the West African monsoon system

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Realistically simulating the West African monsoon system still poses a substantial challenge to state-of-the-art weather and climate models. One particular issue is the representation of the extensive and persistent low-level clouds over southern West Africa (SWA) during boreal summer. These clouds are important in regulating the amount of solar radiation reaching the surface but their role in the local energy balance and the overall monsoon system has never been assessed. Based on sensitivity experiments using the ICON model for July 2006, we show for the first time that rainfall over SWA depends logarithmically on the optical thickness of low clouds, as these control the diurnal evolution of the planetary boundary layer, vertical stability and finally convection. In our experiments, the increased precipitation over SWA has small direct effects on the downstream Sahel, as higher temperatures due to increased surface radiation are accompanied by decreases in low-level moisture due to changes in advection, leading to almost unchanged equivalent-potential temperatures in the Sahel. A systematic comparison of simulations with and without convective parameterisation reveals agreement in the direction of the precipitation signal but larger sensitivity for explicit convection. For parametrized convection the main rainband is too far south and the diurnal cycle shows signs of unrealistic vertical mixing, leading to a positive feedback on low clouds. The results demonstrate that relatively minor errors, variations or trends in low-level cloudiness over SWA can have substantial impacts on precipitation. Similarly they suggest that the dimming likely associated with an increase in anthropogenic emissions in the future would lead to a decrease of summer rainfall in the densely populated Guinea Coastal area. Future work should investigate longer-term effects of the misrepresentation of low clouds in climate models, e.g. moderated through effects on rainfall, soil moisture and evaporation.

#### Poster Session C / 163

### Cloud anomalies associated with the North Atlantic Oscillation and their radiative feedback in observations and the ICON model

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Clouds shape weather and climate by modifying the transfer of radiative energy through the atmosphere. Recent modeling work highlighted the importance of cloud-radiative effects for the mean circulation of the present-day atmosphere and its long-term response to global warming. However,

little research has been done regarding the impact of cloud-radiative effects on the internal variability of the extratropical atmospheric circulation on synoptic to subseasonal timescales. Here, we focus on how clouds and the North Atlantic Oscillation (NAO) couple on timescales of days to weeks. To this end, we analyze correlations between 5-day mean cloud incidence retrievals from CloudSat/CALIPSO and the NAO index for the winters from 2006 to 2011. A positive NAO is accompanied by increased upper-tropospheric cloud incidence of 4 to 7% along the storm track and in the subpolar Atlantic, and decreased cloud incidence of 2 to 4% equatorward of the storm track and of 7 to 10% along the Labrador Sea, southern Greenland and Iceland. In the mid-troposphere a dipole of cloud incidence is evident with positive anomalies in the higher mid-latitudes and the subpolar North Atlantic, and negative anomalies in the lower midlatitudes. Opposite to upper-troposphere anomalies are observed in the lower troposphere. The cloud changes associated with the NAO lead to substantial changes in cloud-radiative effects (CRE). Vertically integrated atmospheric CRE calculated from CERES-SYN1deg, CloudSat/CALIPSO, CERES-EBAF and GERB/SEVIRI reveal a dipole of heating of 10 to 14 Wm<sup>-2</sup> poleward of the storm track and cooling of -10 to -15 Wm<sup>-2</sup> equatorward of it. This dipole suggests a potential cloud-radiative feedback on the NAO that we discuss from the perspective of vertical profiles of atmospheric heating and its impact on the surface pressure tendency. An analysis of ERA-Interim 6-h forecasts reveals that while the sum of diabatic processes contribute to maintain the positive phase of the NAO, CRE act to damp it. This indicates a negative feedback of CRE on the NAO. Following this observational work we further investigate the NAO-cloud relationship in ICON simulations using the cloud-locking method.

Poster Session C / 272

## High-resolution regional superparameterization of OpenIFS with DALES

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We present a superparameterization of clouds, convection and turbulence in the global atmospheric model OpenIFS, using a high-resolution, three-dimensional local model. The local model in our setup is DALES, an atmospheric large-eddy simulation code.

In the superparameterization approach, parameterizations of sub-grid-scale phenomena in a global model are replaced by coupling the columns of the global model to a local model, where the phenomena of interest are explicitly resolved.

Traditionally, superparameterization has been applied uniformly over all columns in the global model. To manage the computational cost, the local models have often been two-dimensional or set up with a rather small number of model columns, limiting the model resolution or horizontal extent. In our approach, the superparameterization can be enabled inside a designated region, leaving the regular parameterization in use on the outside. The regional selection of columns for superparameterization adds flexibility in balancing the computational cost. In the current study it enables us to run three-dimensional high-resolution local models covering the full horizontal extent of the global model's columns, while limiting the number of superparameterized columns to control the total computational cost.

With high-resolution local models, the local models usually consume a major part of the computing resources. We show how the simulation can be accelerated by reducing the spatial extent of the local models and by employing the mean-state-acceleration technique to accelerate the time development.

As a demonstration of our superparameterization setup we show a simulation run over the Netherlands, and compare the cloud fields from the simulation with observations from MODIS and Cloudnet.

The model coupling is implemented in Python, which makes testing and development flexible. Both OpenIFS and DALES are written in Fortran. We have created Python interfaces to both models using the OMUSE framework. These interfaces are now included in the open-source OMUSE program, and can thus be used also in other projects.

#### Poster Session C / 231

### The effect of representation of boundary layer mixing on the simulation of the mid-level clouds over Sahara

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The ubiquitous presence of a thin layer of mid-level clouds over the Sahara desert has been recognised. CMIP5 models systematically fail to simulate these clouds over the Sahara desert. These clouds may play an important role in the cloud feedbacks and regional surface energy budget with important implications to regional meteorology.

In this study, we evaluated the ability of Community Atmosphere Models (CAM5 and CAM4) to simulate these clouds. These models present a unique opportunity since they have different parameterisation schemes for the boundary layer processes, radiation and shallow convection. Both models fail to capture the seasonal mean cloud fraction (2-5 %) over the desert compared to observations (15%). The grid-by-grid evaluation of these models indicated that CAM5 is capable of formation of thin mid-level clouds and its seasonal and diurnal cycles, except CAM5 fails to capture spatial structure and frequency accurately. The CAM4 failed to simulate the mid-level clouds. The degree of vertical mixing of water vapour and the representation of boundary layer (BL) height controls the mid-level cloud fraction in these models.

To further understand the mechanism we modified the vertical profile of water vapour in the BL during a part of the day to represent homogeneous mixing in the boundary layer over desert. In CAM5, such mixing leads to formation of clouds comparable to observations while in CAM4 it leads to formation of deep clouds and modification of the local precipitation. In CAM5, the mid-level clouds form above the maximum level of imposed mixing which suggests that modification of water vapour profile enhances the longwave cooling fluxes above the boundary layer to facilitate the mid-level cloud formation.

#### Poster Session C / 311

### The role of internal circulations on precipitation intensities in a cloud-resolving model

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Large-scale atmospheric circulations can affect the strength of local convection by redistributing moisture and heat in horizontal and vertical directions, and by modulating the interactions between

different regimes of precipitation. One mode of interaction of interest is the role of shallow convective mixing on the vertical redistribution of moisture in the lower troposphere, which is known to affect convective properties of tropical convergence zones in global climate models.

In this project, we use simulations of convective organization as a proxy for atmospheric circulations internal to the tropics, and quantify their role on the distribution of rain. We compare cloud-resolving simulations over a 1000km domain in stable conditions of radiative-convective equilibrium at various surface temperatures. Compared to disorganized convection, convective aggregation induces stronger precipitation extremes that increase faster with warming, at a rate of 14-15%/K. This super-Clausius-Clapeyron rate is caused by changes in the horizontal partitioning of moisture that favors a faster increase in humidity in the deep convective region and leads to more rapidly intensifying cloud updrafts. Effects of shallow convective mixing are investigated next. The vertical redistribution of humidity by shallow convection is emulated in organized states by adjusting the turbulent eddy diffusivity by a constant factor in the dry environment surrounding the convective cluster. First results show that this effect is likely small in comparison to the role of horizontal heterogeneities that appear in the presence of organization.

We conclude by commenting on possible implications for the intensification of rainfall in the real tropics. Interesting challenges arise while interpreting the results because of a few important mechanisms that cannot be captured in this simplified approach due to modeling limitations.

#### Poster Session C / 146

### Investigate the impact of land surface heterogeneity on moist convection using the ICON-LEM model

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Convective events are the result of different states of the atmospheric modifications due to synoptic scale condition and/or land surface characteristics. A major role in the process chain from land-surface variations, Atmospheric Boundary Layer (ABL) heterogeneity and convection is played by ABL-troposphere coupling – a process that occurs on different scales. The identification, as well as the quantification of this coupling, is important for a better estimation of the occurrence and strength of convection and its influence on heavy precipitation events. Land surface heterogeneity can be defined in terms of differences in soil type, orography, vegetation, and land use etc. These variations along with cloud cover influence the surface turbulent fluxes pattern. Lightning can be taken as a proxy for moist deep convection.

In this study, based on orographic complexities and associated hotspots of convection, we aim at three investigation areas: flat terrain, isolated orography, and complex orography. Suitable days for simulation were selected using the criteria of low wind speed and considerable flash density over the respective areas. The dependence of the diurnal cycle of surface sensible heat flux pattern on the parameters of leaf area index, orography, soil moisture, and net shortwave radiation was measured using the standardized multiple regression coefficients. The source areas of convective cells were identified using the backward trajectory model (LAGRANTO). The atmospheric moisture and heat budget terms have been calculated in order to quantify the coupling. For example, in flat terrain, the source area for convection shows a good correlation with enhanced sensible heat flux pattern and accompanied regions, where the boundary layer is warmer than the surroundings which further induce the formation of secondary circulation system along the lakes of the aimed area. The simulations show a higher boundary layer and faster growth rate over inhomogeneous area in comparison to the homogeneous area. The major energy input comes from the turbulent heat and moisture flux.

#### Poster Session C / 201



## Cold pool vortex rings as the “snow plows” of convective triggering

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New convective cells occur at increased likelihood near cold pool gust fronts – as was shown by observations and high-resolution simulations alike. However, pinning down whether this is due to single gust fronts or collisions of multiple ones is much less settled. Conceptual models show that this very distinction, single vs. multi-CP collisions, may be key to the character of the resulting spatial organization of thunderstorms, and related extreme precipitation events.

We assume that the likelihood of triggering convection scales with the height and strength of the updrafts, generated at the gust front of the CP. To understand, what determines their strength, we consider a conceptual model that decomposes CPs into three players: (1) a cold air downburst that determines the initial potential energy, (2) a peripheral rotating torus – often referred to as a *vortex ring* – and (3) a thin cold air “carpet” in the interior of the torus. The vortex ring could be caricatured as a snow plow shoveling air into the vertical due to its key role in the dynamic interaction of and between CPs. The introduction of a vortex ring allows us to relate the understanding of cold pool collisions back to the more generic process of vortex interaction - a well-seasoned branch of classical fluid dynamics. We use this model to analyze how the initial potential energy is converted into linear and rotational kinetic energy of the vortex ring and finally back into potential energy of the lifted environmental air.

We compare our theoretical vortex ring model to idealized large-eddy simulations in terms of energy budget, radial velocity and the strength of updrafts produced at the gust front and in collisions. These simulations show that the maximum vertical velocities resulting from two colliding CPs are up to a factor three higher than at an undisturbed CP front and extend higher into the atmosphere. Preliminary results also suggest that the CPs spread as coherent structures over times that exceed the lifetimes predicted by conventional models that are based on the assumption of CPs of cylindrical shape. This may be due to the reduced mixing and spatial concentration of energy in the hypothesized vortex ring.

**Poster Session C / 286**

## The transient dynamics of clouds

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Most cumulus parametrisations describe convective clouds as plumes, either in a bulk plume framework or using a spectral approach for clouds of different size. However, large parts of the cloud do not actively contribute to moisture, heat and momentum transport. Rather, this transport tends to be carried by rapidly ascending cores, which can have a ring of vorticity associated with them. These cores may be strongly influenced by the wider cloud environment. Understanding their behaviour is key to both convective parametrisation and identifying deficiencies in simulations where such cores are poorly resolved.

Here, the behaviour of convective cores in idealised environments is studied and compared against integral models based on a plume or thermal as a basic element. Tracer-based techniques are used to determine the core size and the degree and source level of dilution by environmental air, and to assess these diagnostics against integral models. In a moist environment, the cores can be accurately described by a thermal approach. As is consistent with previous studies, the drag on the thermal plays an important role in setting its vertical velocity. In a dry environment, the integral models are

less successful and may need modification. In particular, the thermal's behaviour in the initial phase of development needs to be captured.

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## Scientific wrap-up of the day

**Morning Session: Topic V / 317**

### On the importance and challenges with the representation of momentum transport by shallow convection

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Despite playing a key role in the atmospheric circulation, the representation of surface drag and momentum transport processes has been largely overlooked by the model development community over the past decade, at least compared with diabatic and radiative processes. One of these processes, which has been studied little until recently despite playing a significant role in aspects of the atmospheric circulation is the momentum transport by shallow convective clouds. In this talk, I will discuss the importance of convective momentum transport (CMT) for shallow convection based on global weather prediction experiments where the parametrization of this process is turned off. I will also discuss how Large-Eddy Simulations have been used (i) to look into the caveats of existing CMT parametrizations for shallow convection; (ii) evaluate the influence of low-level wind shear on convection, cloudiness and the character of momentum transport, and better understand the coupling between winds and clouds. Using idealized LES, we will emphasize a first-order effect of large-scale wind shear that is often overlooked, namely, the adjustment of near-surface winds and fluxes via momentum transport. This has important implications for the growth and transitions of cloud-topped boundary layers. Shear also has important secondary impacts on the depth of convection and the height of the trade-wind inversion. Finally, we will highlight differences in convective momentum transport in the sub-cloud layer depending on the presence of clouds overhead, and show how the character of a frictional effect changes.

**Morning Session: Topic V / 99**

### ParaCon's parametrisation of convection at kilometre scales

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I will present an overview of the ParaCon programme's activities on the parametrisation of convection at km-scale resolutions.

ParaCon is a joint research programme between the UK Met Office and NERC-funded University departments to make significant improvements to the representation of convection in models from 100km down to 1km scales.

Within this programme are three parametrisation strands to represent convection at km scales: the first is through a scale-aware mass-flux approach; the second is through a higher-order turbulence scheme; and the third is a novel representation of the dynamical core, in which more than one fluid can be represented in a dynamically-consistent way.

I shall present underpinning research and progress for each of these approaches, including the validity of representing convection as a heating term at these scales, choosing a partition between the convecting and non-convecting flow, and the scale dependence of initiating mass sources, finally outlining how these diverse strands could eventually be unified.

**Morning Session: Topic V / 66**

## Subgrid-scale parameterization using machine learning

Pierre Gentine<sup>1</sup> ; Mike Pritchard<sup>2</sup> ; Yu Cheng<sup>3</sup> ; Stephan Rasp<sup>4</sup> ; Tom Beucler<sup>5</sup>

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Cloud, convection and turbulent parameterizations remain some of the bottlenecks of climate models, limiting our capacity to evaluate climate sensitivity and regional climate changes.

Recent advances in computational capacities have allowed the generation of high-resolution high-fidelity simulations that can resolve many of the processes of interest (e.g., turbulence, deep convection). Direct Numerical Simulations and Cloud-Resolving Models, in particular, can be harvested to define data-driven subgrid-scale models for turbulence and deep convection.

We will discuss two applications of machine learning to turbulent and deep convection parameterization, showing large improvement compared to regular parameterizations.

The presentation will also focus on out-of-sample generability for prediction, spectra, scale-awareness and resolution dependence (e.g. Reynolds number).

**Morning Session: Topic V / 106**

## The Neighboring Column Approximation (NCA) – a 3D Heating Rate Parameterization for Structured and Unstructured Grids

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In the thermal spectral range, emission and absorption of radiation by clouds and the atmosphere are the main radiative interactions. This results in cloud side and cloud top cooling and in modest warming of the cloud base for finite clouds (e.g. cumulus clouds). Both effects were shown to have an impact on cloud formation, changes in dynamics of the system, cloud field organization or the strength of extra tropical cyclones.

Cloud side cooling effects in the thermal spectral range are often neglected in current large eddy simulation (LES) models where radiation is generally calculated with the independent column approximation. For the accurate calculation of these thermal heating and cooling rates, fast 3-dimensional radiative transfer models are necessary: These models (usually Monte Carlo) are too expensive to be used in LES models which shows the need for less expensive 3D approximations. The Neighboring Column Approximation (NCA) was, to our knowledge, the first approach to overcome this lack in 3D thermal radiative transfer parameterizations. Developed in 2015, it is by now implemented in several LES models and was applied successfully. Its computational efficiency (computational time only a factor of 1.5-2 compared to a 1D approximation) made it possible to investigate the impact of 3D thermal radiative effects on clouds in a large domain for the first time. Here it could be shown that 3D thermal radiative effects can change the organization of the cloud field and cloud dynamics (e.g. updraft velocities). With the continuing development of cloud models and the increase in computational power, model resolution increases further, which enhances the necessity of 3D radiative transfer parameterizations.

Here, we present an update of the original NCA suitable to be used on structured (rectangular) and unstructured (triangular) grids (e.g. for the ICON-LEM model).

**Morning Session: Topic V / 91**

## **The Continental-Scale Soil-Moisture Precipitation Feedback at Convection-Resolving Resolution**

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In weather and climate simulations, the feedbacks between soil moisture and precipitation are sensitive to the details of the convection parameterization schemes employed. As observation-based and modeling studies have repeatedly shown, mesoscale circulations emerging along localized soil-moisture gradients frequently initiate deep convective systems on the dry side of the gradient. In convection-parameterizing simulations, these circulations are not fully captured, and the representation of the feedback is thus associated with considerable uncertainty. For instance, in some previous studies, convection schemes yield a positive feedback, but a negative feedback if convection is represented explicitly. However, due to the substantial computational cost involved, simulations examining the processes at convection-resolving resolution were so far limited to sub-continental computational domains and season-long integration periods.

The capabilities of current heterogeneous supercomputers enable conducting decade-long simulations, at resolutions allowing explicit representation of the involved circulations. We exploit these capabilities to perform continental-scale soil-moisture perturbation experiments at convection-resolving (2.2 km) and convection-parametrizing resolutions (12 km). The simulations are driven by the ERA-Interim reanalysis and cover ten perpetual summer seasons (MJJJ, 1999-2008) on a computational domain spanning continental Europe (1536x1536x60 grid points).

Results indicate an increasingly dominant role of moisture advection if soil moisture anomalies exceed a spatial scale of about 100 km, leading to an overall positive feedback and considerable precipitation sensitivity along mountain ranges. While convection-parameterizing and convection-resolving simulations lead to a similar spatial distribution of the soil-moisture induced precipitation change, differences arise regarding the sensitivity of the feedback, and w.r.t. frequency and intensity

distributions. To better understand these differences, ensembles of idealized convection-resolving simulations with simplified lower and lateral boundary conditions are additionally performed. Notably, the role of the horizontal advection, the spatial scale of the soil moisture anomaly and the domain size are systematically tested.

**Morning Session: Topic V / 103**

## **Water vapor variability in the tropics from modelling and airborne lidar**

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The distribution of water vapor is closely connected to the appearance of shallow and deep convection, interacts with the circulation through radiation, and affects the intensity of cloud feedbacks. High horizontal and vertical variability of water vapor is omnipresent in the tropics but poses challenges for weather and climate models. In this study we compare high-resolution simulations and airborne lidar measurements to help elucidate these complex interactions. Both the ICON simulations and the WALES lidar measurements were conducted for the NARVAL campaign, which took place in December 2013 in the Northern Tropical Atlantic east of Barbados. ICON simulations are available at several grid spacings down to 300 m and include the area and period of the flight domains. Given a vertical lidar resolution of about 300 m and the capability to obtain profiles within cloud gaps of about 3 km minimum size, the WALES lidar onboard the research aircraft HALO is able to detect small-scale vertical moisture gradients and thin dry layers. This combination of remote sensing characteristics and high-resolution modelling allow unprecedented insights into water vapor distributions in the vicinity of shallow (trade clouds) and deep convection (ITCZ).

Across model grid spacing from 300 m to 2.5 km, ICON shows a good skill in reproducing lidar measurements of water vapor variability and distribution in the tropics. An exception of this is a persistent moist model bias near the shallow cumulus cloud top, which is connected to the strength of the humidity inversion at the same height and possibly an artifact of too strong vertical diffusion in the model. Despite the overall good agreement in water vapor, cloud fraction depends strongly on model resolution and also has a larger uncertainty in the observational estimate. The simulated cloud fraction decreases with resolution and tends to agree better with observations for high resolution simulations.

**Morning Session: Topic V / 172**

## **How cold pools systematically organize convection**

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We present a zero-parameter model for the diurnal self-organization of convective clouds by cold pools. As an initial condition, the model assumes a two-dimensional area containing a random collection of points, that is, spontaneously erupting precipitation cells. From each point, a circle spreads with radius increasing linearly with time,  $R=vcpt$ , mimicking the advance of a cold pool gust front. Here,  $vc$  is the gust front speed and  $t$  is time.

Subsequent cells no longer erupt spontaneously: they only occur, when three circles meet, a geometric feature we motivate by large-eddy simulation analysis. In short, the intersection of three gust fronts constrains the degrees of freedom so profoundly, that only a vertical escape is possible – hence an updraft must result, triggering a new precipitation event.

Our model leads to the natural concept of clouds as occurring in “generations”, and gives a simple explanation for why spatial scales increase linearly with time in diurnal cycle LES simulations, that is,  $l(t) = l_0 + v_{cp} (1-r) t$ , where  $l_0$  is the initial scale, set by the number of spontaneous cells, and  $r$  is the replication rate from generation to generation, a number that dynamically develops, that is, self-organizes, to  $r \approx .85$ .

Along with increasing spatial scales, we generally find increasing precipitation intensities, as the diurnal cycle progresses. We comment on ways, in which our simple model can explain such intensity increases, hence, in principle, kick-starting a theory for the self-organization of extreme precipitation in shear-free environments.

We further comment on applicability of this simple model to radiative convective equilibrium simulations and convective self-aggregation.

**Morning Session: Topic V / 151**

## Understanding Cold Pool Dynamics through a Lagrangian Approach

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Because of its great societal impact, predicting how precipitation will respond to climate change is a task of considerable importance. In order to achieve this ability, however, a robust, quantitative understanding of the dynamics of precipitating systems is first necessary. In this talk, I will illustrate how a Lagrangian perspective can be used to take important steps in this direction. The main focus will be on the dynamics of cold pools, which, although neglected by most convective parameterizations, are crucial ingredients of deep convective systems. I will start by showing how Lagrangian particles can be used to study key properties—such as the initial height and the driving mechanisms—of the precipitation-driven downdrafts that give rise to cold pools and set their properties. I will then discuss how a careful examination of the history of Lagrangian particles can shed light on the sources of the positive moisture anomalies that develop around cold pools during their life cycle and that play a role in the formation of new clouds. I will then introduce a novel method to identify and track cold pools in a numerical model based on Lagrangian techniques, and show how this can be employed to quantify the importance of different mechanisms by which cold pools trigger new convective cells. Finally, I will discuss ongoing work on the statistics and the dynamics of cold pool collisions, and on the use of the Lagrangian methods I developed to study severe weather systems, such as supercell storms.

**Morning Session: Topic V / 230**

## An emulator approach to adjustments and buffering in stratocumulus

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The radiative forcing due to aerosol-cloud interactions (ACI) remains the most uncertain anthropogenic forcing of the climate system. Its uncertainty is rooted in our insufficient understanding and representation of subgrid-scale processes, in particular convection, entrainment, and precipitation formation in shallow clouds. When the cloud system is perturbed by aerosol, the various processes internal to the system may adjust in a way that modifies the overall impact of the perturbation. These so-called adjustments have been hypothesized to weaken, or buffer, the response that would have occurred in the absence of adjustments.

We synthesize a simple picture of the radiative effect of ACI in stratocumulus (Sc) from the detailed process-representation of 159 large-eddy simulations (LES). These simulations of nocturnal Sc vary in their initial conditions for temperature, moisture, boundary layer height and aerosol concentration. Our synthesis is based on Gaussian process emulation, a technique related to machine learning. While emulators have so far been used to investigate the effect of model parameters, we apply emulation to evolving cloud field variables. We thus emulate process rates that govern the temporal evolution of liquid water path (LWP) and cloud droplet number concentration  $N$ . These process-rate emulators allow us to study Sc as a low-dimensional dynamical system in the spirit of Lilly's mixed-layer model. In contrast to the mixed-layer model, our dynamical system represents the full complexity of an LES model. It constitutes a simplified but not idealized representation of the LES, from which it emerges.

Our analysis highlights that ACI cannot be discussed without considering Sc cloud fields as systems that evolve in time. The systems evolve to two steady states: one a non-drizzling, high cloud cover and high  $N$  state, and the other a low cloud cover and low  $N$ , drizzling state. Both feature domain mean LWPs of about  $60 \text{ g/m}^2$ . We distinguish between the natural evolution to these steady states, and adjustments that would occur if the system were to be perturbed. We show that adjustments are unlikely to be detectable when the natural evolution is fast. The detectability of adjustments increases as a system approaches its steady state. At the same time, adjustments in the steady state are small because steady-state LWPs are largely independent of the aerosol condition. Overall, our analysis points to a small contribution of adjustments in general and buffering mechanisms in particular to the radiative effect of ACI.

**Morning Session: Topic V / 157**

## **A simulator-based satellite dataset for using machine learning techniques to derive aerosol-cloud-precipitation interactions in models and observations in a consistent framework**

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Aerosol-Cloud-Precipitation Interactions (ACPI) remain a large uncertainty in understanding Earth system dynamics. Observational constraints at the process level are highly desirable, but two outstanding challenges exist when comparing models and observations: (1) ACPI are typically estimated inconsistently between models and observations which can compromise the validity of the ACPI metrics, and (2) ACPI process representation in models is often developed/calibrated based on one cloud regime while the process operates globally, producing biases in other regimes. Here we show that both challenges can be addressed by using machine learning techniques to derive ACPI from a newly developed observational dataset. We construct a new satellite-based data product that consists of

aerosol, cloud, precipitation, and meteorological information, where aerosol, cloud, and precipitation fields are produced by the same algorithms as those implemented in simulators in models, so that inconsistencies between models and data are minimized and that results from data analysis can be directly applied to models. Deep learning algorithms are then employed to identify other significant aerosol, cloud, precipitation, or environmental variables that have been conventionally overlooked in constructing ACPI metrics or process representations. We will present the new formulation (or “rules”) regulating ACPI, instead of finding an optimal set of parameters/coefficients for an incomplete formula. Results can provide a holistic view of processes regulating ACPI in various conditions, and quantify the systematic bias due to the structural deficiency of current models.

**Morning Session: Topic V / 204**

## **Statistics of polarimetric radar variables in the melting layer to improve its representation in atmospheric models**

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Polarimetric observations provide a wealth of information on precipitation microphysics, which can be exploited to improve parameterizations of numerical weather prediction models. In particular, the parameterization of ice microphysical processes, which still are not treated adequately in NWP models, may benefit from such observations. E.g. melting processes are not well reproduced in bulk microphysical models partly because of the typically missing mixed-phase hydrometeor categories. Time series of Quasi-Vertical-Profiles (QVPs) from 52 stratiform precipitation events observed with the polarimetric X-band radar BoXPOL in Bonn/Germany between 2013 and 2016 have been statistically analyzed in order to provide a climatology of polarimetric variables in the melting layer to evaluate and to finally improve the melting process in atmospheric models.

In the COSMO/ICON microphysics parameterization, meltwater from snow, graupel, and ice is instantaneously shedded into the rain class, causing too small and too few remaining frozen particles in the melting layer. The current version of the forward operator EMVORADO estimates a melted fraction as function of temperature and particle size as part of the remaining frozen mass without “back-shuffling” some rain water to the particles. This leads to a systematic underestimation of the melting effect in all radar moments.

Reliable estimation of polarimetric variables in the melting layer is key to evaluate the representation of clouds and precipitation microphysical processes in numerical models. The presented polarimetric climatology is the only one including also specific differential phase and backscatter differential phase  $\delta$ . In aggregated snow,  $\delta$  is proportional to the 1st moment of the drop size distribution and thus a very valuable melting layer measure to characterize precipitation flux (other variables are heavily weighted by the few largest snow aggregates) and  $\delta$  is a good indicator of the maximal snow particle size above the freezing level. Distribution of polarimetric variables in the melting layer and correlations between these variables, key for the evaluation of the melting process in the models, will be presented and opposed to synthetic polarimetric profiles based on the COSMO model using a first polarimetric extension of EMVORADO (EMVORADO-POL). To better characterize the melting layer, EMVORADO-POL assumes spheroidal frozen and mixed-phase particles instead of spheres. Finally, first ideas will be presented to first improve the representation of melting in EMVORADO-POL, as a first step towards the inclusion of model microphysics with explicit mixed-phase snow, graupel, and hail in COSMO/ICON in the future.

**Poster Session D / 126**

## **Ice nucleation: CCN- and cloud-regime-sensitivity over HD(CP)<sup>2</sup>-LES resolved Germany.**



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A sensitivity experiment with 2xCCN has been performed for 2. May of 2013 as part of the 156m-resolved Germany-domain HD(CP)<sup>2</sup> simulations. Despite unchanged IN, it shows large increases in ice concentrations (Costa-Suros et al., in prep.). Ice nucleation rates were not output. Via our method to recalculate ice nucleation rates, we explain the large ice concentrations in the 2xCCN simulation. The application of a cloud classification scheme reveals the prevalence of cloud droplet freezing and ice multiplication in deep-convective clouds. We employ both methods also to a new 4D CCN simulation and compare resolutions and variants of microphysics.

**Poster Session D / 43**

## Tracking of convective rain events in idealized and realistic large eddy simulations

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Object oriented analysis methods are increasingly favored tools for statistical evaluations of data sets showing complex convective environments. These could be both model data as well as observations like radar data sets. I present a tracking algorithm that is particularly suited for the study of convective rainfall events and their interaction with neighboring convective cells. While some of these cells just form, grow, and finally disappear without interacting with other cells, others merge with their neighbors to form larger, more intense cells. In particular, repeated merging may be regarded as the preliminary stage of clustering and convective aggregation, as it is e.g. found in simulations of radiative convective equilibrium (RCE).

I will first discuss the properties of the tracking method on the basis of an application to idealized large eddy simulations (LES). For tracks that do not merge or split (termed “solitary”), many of these quantities show generic, often nearly linear relations that hardly depend on the forcing conditions of the simulations, such as surface temperature. Furthermore, I will present a more realistic application on a limited area simulation with ICON-LEM for a domain covering Germany with 600 m grid spacing: In a land use change experiment, the whole domain is afforested by mixed forest, and the feedback on convection is investigated. It was found that convective cells are more intense in the afforested simulation, compared to the control simulation.

An important factor for the organization of convection is the role of cold pools. Similar as the convective cells that they originate from, cold pools can be regarded as individuals. As an outlook, I will discuss a tracking method for cold pools, and speculate how it could be combined with the presented rain cell tracking into one single framework.

**Poster Session D / 202**

## Response of convective boundary layer to 2-D soil moisture heterogeneity: A large-eddy simulation study

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The land surface is heterogeneous in various aspects over a wide range of spatial scales and the atmospheric boundary layer is strongly dependent on the state of the heterogeneous land surface. This study investigates the response of the convective boundary layer to the spatial variation of soil moisture in a mesoscale domain, using large-eddy simulation. The soil moisture heterogeneity in the domain is analytically generated as a function of the Gaussian random field by controlling its power spectral slope. The spectral slope in the wavelength range from tens of meters to a few tens of kilometers in the soil moisture spectrum on a log-log scale. Three sets of two simulations are initialized with heterogeneous soil moisture patterns. The spectral slopes of the three sets of simulations are  $\propto 0$  ( $\propto$  is wave number),  $\propto -2$ , and  $\propto -3$  respectively. In each set, one simulation of a high spatial variance in soil moisture, while the other simulation of a low spatial variance. Moreover, the spatially-averaged values of soil moisture are identical in all of the three sets of simulations. Simulation results show that surface sensible heat fluxes are slightly different between each case, while latent heat fluxes and Bowen ratios are highly modified. Moreover, latent heat flux and surface energy partitioning are more sensitive to the spatial variances of the soil moisture than to its heterogeneity scales. Domain-averaged vertical profiles of potential temperature, specific humidity, and wind velocity are slightly influenced, while the vertical profiles of the variances of these quantities are different significantly between each other.

**Poster Session D / 48**

## Estimation of Cloud Droplet Number Concentration of Shallow Trade-Wind Cumulus Using Synergistic Remote Sensing Measurements.

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The cloud droplet number concentration  $N$  is of major interest for global climate models. Together with the liquid water content ( $LWC$ ) it determines the cloud droplet effective radius ( $r$ ) and therefore the cloud radiative properties. Studies showed that the radiative impact of shallow trade-wind cumuli is highly sensitive to changes in  $N$ . In conjunction with variable  $LWC$  this results in poor model parameterizations not covering the variability of  $N$  and  $LWC$  yet.

Estimates or in-situ observations of  $N$  of trade-wind cumulus for model validation are sparse. Global statistics of  $N$  are averaged over different thermodynamic conditions masking the effect of  $N$ ,  $r$ , and  $LWC$  on the radiative budget of the cloud. Satellite retrievals of  $N$  suffer from uncertainties and strict assumptions. Using the synergy of airborne and ground-based, passive and active remote sensing the uncertainty of  $N$  retrievals can be reduced the gap between satellite-based global averaging and in-situ single cloud sampling can be overcome.

The approach combines spectral solar radiation measurements with passive microwave and active radar and lidar observations. The method has been successfully applied for airborne measurements during the NARVAL-II campaign with HALO of the DLR and will be extended for ship-based observations during the Elucidating the role of clouds-circulation coupling in climate (EUREC<sup>4</sup>A) campaign in 2020.

The common approaches to estimate  $N$  from cloud retrievals based on reflected or transmitted solar radiation are extended by including additional information from passive and active remote sensing. Combined measurements and retrievals of cloud optical thickness,  $LWC$ ,  $r$ , cloud base and cloud top altitude retrieved from the instruments are used. Different parameter combinations are applied in the radiative transfer calculations comparing the influence of each parameter. For NARVAL-II, cloud cases are selected to illustrate the potential and limitations of this approach to estimate  $N$  from airborne remote sensing. A sensitivity study was performed to estimate retrieval uncertainties. For two cloud cases of homogeneous, non-precipitating shallow trade-wind cumuli reasonable values of  $N$  are obtained.

While airborne measurements cover larger areas, they lack of spatial resolution and have difficulties in co-location of the individual instruments. Especially for small scale trade wind cumulus covering only several hundreds of meters the application of the method is limited. Therefore, it is planned to use ship-based observations of similar remote sensing instrumentation during EUREC<sup>4</sup>A to increase

the sensitivity for small shallow clouds. A first feasibility based on test measurements in Leipzig in will be presented.

Poster Session D / 54

## Mechanisms of future extreme precipitation intensification in a convection-permitting model

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Convection-permitting models exhibit considerable added value for the representation of both extreme precipitation in the present climate and future changes therein in a warmer climate. In particular for sub-daily precipitation extremes, convection-permitting models often show a stronger response to warming than that found in coarser models with parametrized convection. Due to their explicit simulation of key processes, e.g. deep convection, convection-permitting models also offer an ideal platform for studying the different physical mechanisms which may lead to the future intensification of extreme precipitation.

Using a regional domain centred on the catchment of the River Wupper (western Germany) – a key study region of the H2020 project BINGO – we perform historical and future (RCP8.5) climate simulations at 0.02° (~2.2 km) resolution with the COSMO-CLM model; the GCM is MPI-ESM-LR. We find a range of extreme precipitation scalings, ranging from sub- to super-Clausius-Clapeyron. Taking the summer season, we explore the physical mechanisms behind the deviations from Clausius-Clapeyron scaling, with particular focus on thermodynamic and dynamic contributions, and their relative importances.

Poster Session D / 130

## Evolution and scale dependency of total water variability in convective situations

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Convection and microphysics, in particular precipitation and sedimentation, have a very large impact on the water budget of the upper troposphere. High resolution simulations give us information on the variability and the spatial and temporal scales on which the total water field is changing. This variability aggregated over larger areas is the basis for the representation of clouds and precipitation in lower resolution models. We investigate whether the model resolution required for estimating the total water variability depends on the synoptic situation. How big is the error when approximating the total water distribution by a distribution function used in a lower resolution model and what does this error mean for cloud cover and microphysical processes, which are inferred from the distribution function?

We use high resolution ICON-LEM simulations to investigate the scale dependency and time evolution of the second and third order moments of the total water PDF (variance and skewness), which are closely connected to microphysical processes and are strongly influenced by convective activity. We focus on the cirrus regime, with particular attention on the influence of convection.

## Poster Session D / 182

**A statistical approach to evaluate the parametrisation of turbulence in convection-permitting models using radar-retrieved eddy dissipation rates.**Author(s): Matt Feist<sup>1</sup>Co-author(s): Chris Westbrook<sup>1</sup>; Peter Clark<sup>1</sup>; Thorwald Stein<sup>1</sup>; Humphrey Lean<sup>2</sup>; Alison Stirling<sup>2</sup><sup>1</sup> *University of Reading*<sup>2</sup> *UK Met Office*

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The effects of turbulence on the evolution of convective clouds remains uncertain both in observations and in numerical weather prediction (NWP) models. Turbulent processes remain parametrised in convection-permitting models (CPMs), and simulated clouds remain highly sensitive to the configuration of sub-filter turbulence schemes. It remains unclear how valid the assumptions implicit in these schemes are for CPMs. This study aims to evaluate their performance using observations. Eddy dissipation rates ( $\epsilon$ ) are retrieved in range-height radar data by applying a comprehensive method to infer the turbulent component of the Doppler velocity spectrum variance. The accuracy to which  $\epsilon$  can be estimated is dependent on accurate assessment of all other processes contributing to Doppler variance. Hydrometeor fall-speed variances are shown to be negligible when sampling at elevations lower than  $11.5^\circ$ . Shear is calculated directly by applying a linear velocity model to Doppler velocities. New equations are presented to account for variance from azimuthal shear – an unseen dimension in range-height scans. Resulting values of  $\epsilon$  are insensitive to the scale over which shear is calculated. By applying this method throughout large datasets of observations collected over the southern UK using the ( $0.28^\circ$  beam-width) Chilbolton Advanced Meteorological Radar (CAMRa), a thorough statistical analysis of  $\epsilon$  in observed clouds suitable for model evaluation is presented for the first time. Values of  $\epsilon$  range from  $10^{-3} - 10^{-1} m^2 s^{-3}$  in shallow “shower” clouds and from  $10^{-3} - 1 m^2 s^{-3}$  in more vigorous “deep” clouds. Turbulent intensity increases with height in deep clouds while remaining approximately constant in shower clouds. Significant positive correlations are demonstrated between  $\epsilon$  and many cloud characteristics; in particular, updraft velocity and shear. Coherent features of  $\epsilon$  are found to have typical spatial scales of 0.5 – 1 km. Results are compared with equivalent statistics derived in 100-m and 55-m grid-length Met Office Unified Model simulations of the observed cases to evaluate the Smagorinsky-Lilly sub-filter turbulence scheme. Simulated turbulence is characterised by small, intense regions of  $\epsilon$  that are more strongly co-located with shear around updrafts than is observed. The 95th and 99th percentiles of model  $\epsilon$  are one and two orders of magnitude larger than observations, respectively, with similar median values. Values of  $\epsilon$  increase consistently with the model mixing length. The indication that  $\epsilon$  remains insensitive to changes in grid-length suggests that 100-m grid-length was sufficient to resolve an inertial sub-range in these simulations.

## Poster Session D / 289

**Radar reflectivity in convective-scale simulations with COSMO/ICON and in observations during a highly convective period**Alberto de Lozar<sup>1</sup>; Ulrich Blahak<sup>2</sup>; Axel Seifert<sup>1</sup><sup>1</sup> *Deutscher Wetterdienst*<sup>2</sup> *Deutscher Wetterdienst*

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The Deutscher Wetterdienst (German Meteorological Service, DWD) operates a dense network that consists of 17 C-band radar sites. This dense radar network assures a complete coverage over Germany and part of the bordering countries. Radar measurements are available every five minutes for ten scanning angles, thus providing dense temporal and vertical information.

Our objective is to use the radar signal to evaluate the performance of different convective-scale models and physical parameterizations. To this end, we have performed several simulations with ICON and COSMO at 2.8 km resolution using different microphysical schemes (one-moment vs. two-moments). Both models use similar “physics packages” but very different dynamical cores. All simulations are driven by the same boundary conditions from the ICON-EU analysis fields. The simulated period is spring/summer 2016, which is characterized by heavy convection over Germany.

The simulated fields are analyzed with the forward operator EMVORADO that simulates the 3D measurement process of the equivalent radar reflectivity factor. EMVORADO mimics the scanning strategy of the DWD radars, which allows for a direct comparison. We compare the combined height/reflectivity histograms. In general all models perform well, but the two moment scheme is better for the high reflectivities that characterize convective cores. Our preliminary results show that changing the model, and thus the dynamical core, has a lesser impact than changing the microphysical scheme. Further work will aim to investigate object-oriented properties of convective-cells, like volume, projected area or lifetime.

Poster Session D / 120

## Momentum mixing and gustiness under different convective conditions and cloudiness over Cabauw

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Convective momentum transport (CMT) measurements are very scarce yet important to constrain the impact of CMT on the wind profiles, variability of the wind and possibly the large-scale circulation.

In this study we ask how wind profiles and momentum fluxes change with cloudiness and convection during daytime hours. Stronger convection will likely cause a better mixed 200m layer. Convection strength will largely depend on insolation and hence cloud cover, time of the day and season. Furthermore, the variance in wind speed is expected to change under different cloud fields: e.g. stronger/more organised downdraughts that are associated with cumulus clouds can enhance the variability of the near-surface wind speeds.

A nine-year-long data set of the Cabauw observatory containing 10-minute interval measurements of wind, temperature, humidity and fluxes from the 200m tall tower are used together with cloud base statistics from a ceilometer. The data is conditionally sampled on cloud cover, surface buoyancy flux or wind shear in the lowest 200m and averaged, while being mindful of the strong seasonal and diurnal signal.

Per year ~40 textbook shallow cumulus days are found. They are climatologically very alike clear-sky days, but with slightly better mixing and somewhat larger wind speeds near the surface. An additional large number of days have (deeper) cumulus congestus, which are typically more overcast. Albeit overcast days have less insolation and usually have larger wind speeds, lower surface buoyancy flux and less mixing than clear-sky days, there are individual overcast days that are more convective and have (quite) well-mixed wind profiles. No general dependency of surface buoyancy flux on cloud cover has been found for shallow cumulus days, on overcast days on the other hand, a clear decrease of surface buoyancy flux with cloud cover is observed.

Conditionally sampling on 200m wind shear, we found that days with low shear have larger buoyancy flux and less shear during the nights. During daytime, days with better mixed wind profiles have accelerating winds in the entire 200m layer. Momentum transport profiles will be examined

on different behaviour on days with different 200m wind shear. Furthermore, one year of high-resolution LES hindcasts is verified on cloud and wind representation. For well represented days, the LES is used to a) evaluate the role of CMT in the momentum budget and b) to find the origin of the acceleration of the wind in the 200m layer: convective up- or downdraughts or large-scale processes.

#### Poster Session D / 148

### Cloud size distributions in observed and simulated shallow cumulus cloud fields

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Clouds exhibit sizes that range over several orders of magnitude, making their proper representation in climate models challenging. Given the general strive for ever increasing resolution in climate modelling, we investigate the potential improvements such an increase in resolution offers in the fidelity of simulated cloud size distributions in comparison to satellite validation data.

Cloud size distributions have been intensely studied in the past due to their relevance in cloud parameterization schemes. The fitted shape of cloud size distributions varies strongly among past observational and modelling studies on fair weather cumulus. We reveal an inconsistency in describing the size distribution in past studies and show that a properly estimated scaling parameter of a power law provides an adequate tool to characterize cloud size distributions.

We derive a reference cloud size distribution from high-resolution ASTER imagery (15 m) and compare it to distributions derived from lower resolution MODIS images (1 km). In ASTER images, a large peak in the cloud size distribution is found at the smallest sizes below a characteristic scale break size of about 600 m. Such small clouds fall into the subpixel range and thus are not fully resolved in MODIS images. However, we can contrast cloud size distributions above the scale break from both satellite datasets. Similarly, we exploit recently performed ICON simulations and compare cloud size distributions from high resolution ICON LEM simulations (150 m) with those from lower resolution ICON simulations (2.5 km) that were conducted within the DYAMOND project.

#### Poster Session D / 266

### Modeling Mesoscale Convective Systems and their Interactions with the Large-scale Environments

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Mesoscale convective systems (MCSs) are responsible for ~60% of summer rainfall in the U.S. Great Plains and 50-60% of tropical rainfall. Deficiency in representing MCSs contributes importantly to climate model biases in simulating precipitation and its diurnal variability over the central U.S. and

tropical circulation, with important implications for modeling the regional and global water cycles. In the past decades, observed increases in springtime total and extreme rainfall in the central U.S. have been dominated by increased frequency and intensity of long-lasting MCSs. Understanding the environmental conditions producing long-lived MCSs is therefore a priority in determining how the characteristics of precipitation may change in the future. Long-lived MCSs produce distinct top-heavy latent heating that provides dynamical feedback through generation of potential vorticity (PV). Convection permitting simulations from regional and global variable resolution models are used to understand the large-scale environment that supports long-lived MCSs and the local and remote influence of MCSs on atmospheric circulation. Using a newly developed MCS tracking algorithm to identify the PV coinciding with a tracked MCS, we will quantify the upscale effect of MCSs through their PV anomalies to shed light on biases in large-scale circulation that may result from model biases in simulating MCSs across a range of model resolutions.

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## Simulations of North Atlantic Hurricanes in Stretch-NICAM with different horizontal resolutions

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Numerical models, and especially climate models, struggle with reproducing tropical cyclones. A reason for this is that the horizontal resolution required is rather high, which comes at a high computational cost.

The Nonhydrostatic ICosahedral Atmosphere Model NICAM has been shown to reproduce tropical cyclone activity reasonably well in global simulations with a uniform horizontal resolution of 14 km. However, the North Atlantic showed notable deviations from nature. This study aims to assess whether an even higher resolution is beneficial to the quality of the simulation results, and where an increased resolution would be the most beneficial.

To improve on previous work, NICAM is used with a stretched grid, which allows a locally higher resolution at the expense of the resolution on the other side of the globe. The focal point is placed within the North Atlantic, at the center of the Gulf of Mexico, where tropical cyclones can intensify greatly, the center of the main development region, where the majority of tropical cyclones spawn, and the center of the combination of both regions, in a series of simulations.

The resolutions used are 14 km and 7 km at the focal point, in two series of simulations. Furthermore, the grid spacing does not exceed 20 km anywhere in the tropical North Atlantic in the simulations using 14 km at the focus, and does not exceed 10 km anywhere in the North Atlantic in the simulations using a resolution of 7 km, as a spacing of more than 20 km might fail to properly produce and maintain intense tropical cyclones.

To allow for a comparison to nature, the simulations are nudged towards 6-hourly ERA5 data from the beginning of May to the end of November for the year 2017, as this year contained a number of intense Hurricanes. The nudging is only applied outside of the North Atlantic, to still allow for a free simulation in the region of interest. 6-hourly ERA5 sea surface temperature is prescribed as well.

The number of produced storms and the accumulated cyclone energy are compared to nature to assess how beneficial an increased resolution is in different regions, and what the benefit of a doubled resolution is.

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## Physically constrained stochastic shallow convection in realistic kilometre-scale simulations

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A scale-aware stochastic approach is developed to parameterize shallow cumulus clouds on the kilometre-scale model grids. It is based on the stochastic subsampling of the cloud number and cloud-base mass flux distributions of shallow cumulus clouds. As a result of this sampling the distribution of the total mass flux in model columns is scale-aware, with a shape that changes from a normal-like on the coarse grids toward a long-tailed distribution on kilometre scales. The major challenge that development of such a parameterization faces, next to the need for an adequate formulation for the convective gray zone, is the coupling with the model dynamics. Under-resolved convective circulations that emerge as a solution of the model dynamical equations in the gray zone should not be allowed to force the subgrid convective response at the grid column level, but the averaged quasi-equilibrium forcing has to be imposed instead. As a result of such a forcing and the stochastic sampling, the subgrid convection will take the control over the under-resolved circulations and change their characteristics and behaviour.

We test the stochastic parameterization in one realistic case over land and one realistic case over the ocean using the ICON model on resolutions from 1 to 10 km. The stochastic model improves the representation of convection and clouds compared to the deterministic scheme, but also compared to the simulation without shallow and deep convection parameterizations. The stochastic sampling introduces variability from the subgrid scales that acts on the model dynamics and changes the structure and strength of the under-resolved convectively induced secondary circulations.

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## **Three Dimensional Radiative Transfer in ICON-LEM – Methods and Impact on Cloud Evolution and Precipitation**

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Recent studies have shown that the effects of three dimensional radiative transfer may impact cloud formation and precipitation.

While one-dimensional solvers are favoured due to their computational simplicity, they do however neglect any horizontal energy transport.

The 1D approximations neglect three dimensional effects such as cloud side illumination and the displacement of the cloud's shadow at the surface.

This has a detrimental effect on the results of high resolution simulations.

3D radiative transfer has the potential to considerably change the boundary layer dynamics, the evolution of clouds, their lifetime and precipitation onset.

To this date, studies that investigate the influence of 3D effects on realistic NWP settings are rare, primarily because there haven't been 3D radiative transfer solvers around that were fast enough to be run interactively in a forecast simulation.

For that purpose we adapted the TenStream solver (parallel 3D radiative transfer solver for LES) to unstructured meshes and coupled it to ICON-LEM.

We will present the new solver in the context of ICON-LEM simulations, the methodologies used and its characteristics.

Furthermore, using a case study over Germany, we present a first analysis of the differences between ICON-LEM simulations driven by 1D as-well as 3D radiative transfer.

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## Retrieving cloud microphysics using combined radar and radiometer observations from the NAWDEX joint flight measurement campaign

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As part of the North Atlantic Wave Guide and Downstream Impact Experiment (NAWDEX) a joint flight of the HALO, SAFIRE Falcon and FAAM BAe 146 research aircrafts has been performed providing a wealth of collocated remote sensing observations of a mid-latitude cloud system. In this study, active and passive microwave observations from the joint flight are combined in a variational retrieval aiming to determine the microphysical state of the observed cloud at unprecedented detail.

The Atmospheric Radiative Transfer Simulator (ARTS) has been used as the forward model to implement a variational cloud retrieval that allows consistent treatment of scattering and absorption effects in the forward simulations of radar and radiometer observations. The use of radar observations at two frequencies (35 and 95 GHz) combined with passive microwave and sub-millimetre observations allows retrieving an additional degree of freedom of the particle size distribution of cloud hydrometeors, which otherwise would have to be determined from a priori knowledge and kept fixed during the retrieval. In addition to that, the combined measurements allow the distinction of cloud phase and thus permit the retrieval of cloud properties even in the mixed- and liquid-phase regions of the cloud. The combined retrieval is validated against in situ measurements taken by the FAAM aircraft during the same flight. The effects of the assumed ice particle shape on the retrieval together with observations from the FAAM's imaging probes are used to investigate to what extent the observations actually constrain the shape of ice particles in the observed cloud system.

**Poster Session D / 98**

## Observation of ENSO linked changes in the tropical Atlantic cloud vertical distribution using 14 years of MODIS observations

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One of the major sources of uncertainty in climate projection is the cloud radiative forcing (CRF). A better understanding of the cloud vertical distribution (CVD) and its relationship to anthropogenic forcing is one crucial point on the way towards a better representation of CRF in climate models.

The moderate resolution imaging spectroradiometer (MODIS) aboard NASA's Terra and Aqua satellites, provides consistent well established data-sets of cloud physical and optical properties from 1999 to date on a high temporal and spatial resolution (on climate scales).

In this study, we used 14 years (September 2002-September 2016) of Aqua MODIS L2 collection 6 cloud products to analyze cloud variability in the tropical Atlantic ocean and linking these satellite observations to large-scale dynamics. We focused on temporal changes and regional differences of cloud top height (CTH) and cloud fraction (CF). The latter was subdivided into low cloud fraction (LCF), middle cloud fraction (MCF) and high cloud fraction (HCF).

The analysis of in total 168 monthly means revealed, despite of a significant increase in AMSR-E

level-3 domain-averaged sea surface temperatures (June 2002-October 2011), no significant trend in the domain-averaged CTH and CVD over the investigated period. A negative correlation between El Niño Southern Oscillation (ENSO) and the high cloud amount was found. In the time period going from a La Niña to an El Niño event, the HCF decreases, resulting in lower mean CTH. This observed relationship in the regional mean was found to be strongest in regions with large-scale vertical upward movements. We related these observations to changes in the large-scale vertical upward movements, which possibly occur due to an east-ward shift and weakening of the Walker Cell (and the Atlantic Hadley Cell) during the transition from La Niña to El Niño conditions (e.g. Klein et al., 1999; Wang, 2004). As climate projection show similar changes in the tropical Atlantic circulation in a warming climate (e.g., Vecchi and Soden, 2007; Bayr et al., 2014; Hu et al., 2018), large ENSO events could be used as a large "experiment" for possible effects of the global warming on the ocean-atmosphere dynamics and the CRF in the tropical Atlantic.

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### AROME-OM : Météo-France NWP Models in Tropical Regions

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Météo-France provides the main French overseas territories (Guadeloupe, Martinique, French Guiana, La Réunion, New Caledonia, and French Polynesia) with forecast products from both global and regional numerical weather prediction systems.

Five new regional systems, using AROME model, have been deployed in early 2016, bringing an important added value for both weather and cyclone forecasting. The AROME model has a non-hydrostatic dynamical model core and detailed moist physics designed for kilometer-resolution forecasts ; it has been in operations over Western Europe since 2009.

Each of the five domains covers an area ranging from 1250 to 4000 km wide. The vertical resolution is characterized by 90 vertical layers starting at 5 m, and a regular 2.5-km resolution is used on the horizontal, allowing explicit deep convection. This first operational version of the Tropics AROME models uses deterministic global model from ECMWF (HRES) as initial conditions and coupling model. Forecasts at +42h of lead time are performed everyday four times a day.

The performance of these Arome systems will be shown on a winter situation for further use during the EUREC4A and Grey-Zone projects.

#### Poster Session D / 188

### Combining models of different complexity and triple-frequency measurements to gain further insights into the aggregation process of ice crystals

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Two-moment microphysics schemes, such as the Seifert-Beheng scheme (SB) implemented in the large eddy version of the ICOSahedral Nonhydrostatic model (ICON-LEM), are better able to realistically represent cloud microphysics compared to single-moment schemes. However, even two-moment microphysics schemes still have problems in reproducing major ice microphysical processes such as aggregation.

Recently available multi-frequency radar observations at the Jülich Observatory of Cloud Evolution (JOYCE) have been shown to be very sensitive to the growth of aggregates. In order to utilize these observations, the Passive and Active Microwave TRANSfer (PAMTRA) forward operator has been recently adapted to SB and Predicted Particle Properties (P3) scheme (which is available as an alternative scheme in ICON-LEM) implemented in ICON but also to the output of a very recent 1D Lagrangian super-droplet model (McSnow). This suite of models allows us to identify discrepancies between observations and model in the highly-resolved 3D space with focus on stratiform cases. The 1D model with a super-particle implementation of ice microphysics and also a 1D version of the SB scheme allows us to investigate these differences in more detail and to apply modifications in a very cost-effective way. Any improvements found can then be tested in the 3D ICON which will also enable us to study the relevance of 3D dynamics on certain ice processes.

First comparison of synthetic and real multi-frequency radar observations of a warm front case revealed too large snowflakes preferentially generated near cloud base in the 2-mom schemes. In initial sensitivity studies we were able to relate this discrepancies to the representation of aggregation and inaccurate fall speed assumptions. The Lagrangian 1D model especially enables us to study the history and evolution of the ice particles in high detail. In addition, the explicit modeling of parameters such as fall velocity allows to avoid implicit assumptions in the forward calculations and hence to more directly link observations and model.

**Poster Session D / 138**

## **Deconvoluting thermodynamic and microphysical controls on tropical anvils extent using modeling and observations.**

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The upper level cloud response to warming contributes substantially to the intermodel spread in global cloud feedback. Energetic constraints such as the fixed anvil temperature (FAT) (Hartmann and Larson, 2002) and the stability iris hypotheses (Bony et al., 2016) provide comprehensible conceptualizations of how upper level clouds respond to warming but it remains unclear whether and how microphysical processes modulate these constraints.

In an effort to understand the interplay between large scale circulation and microphysics, we examine the sensitivity of anvil outflow and extent to both SST and the sedimentation velocity of ice in ICON-LEM simulations run to radiative-convective equilibrium (RCE). We rank model columns by IWP and find that the decay rate of IWP against distance from the convective core is always exponential and increases with SST, which is consistent with the stability iris hypothesis. By recognizing that the column integrated advection of ice must balance its column integrated microphysical sink, we quantify the individual variability of the contributions of large scale divergence and ice removal by sedimentation to the decay rate of IWP. We find that with increasing SST, the divergence decreases while removal increases, which results in a recession of the anvil extent with warming.

Observations from the European geo-stationary satellite Seviri over the tropical Atlantic Ocean indicate that the extent of individually tracked anvils correlates with the large scale subsidence velocity at 250 hPa and smaller ice crystals, confirming our modeling findings. However, inter-seasonal variability in SST is too small to decouple the microphysical variability from the impact of SST on anvil extent. This microphysical “noise” can be mimicked in our simulations, where small changes in the

sedimentation velocity of ice can swamp a potential SST fingerprint. Furthermore, we find that observed anvils have far weaker IWP decay rates compared to modeled ones highlighting model shortcomings in producing reliable anvil longevity. This discrepancy can be corrected for by manipulating the sedimentation velocity of ice in the strongly precipitating anvil region just downstream of the convective core. We find that at these very low and observationally constrained sedimentation velocities, anvil extent becomes limited by microphysical removal and not large scale divergence.

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#### Poster Session D / 114

### Preparing for EarthCARE: The use of atmospheric circulation models as a tool for evaluating satellite data

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EarthCARE (Earth Cloud, Aerosol and Radiation Explorer) is a joint ESA-JAXA satellite mission that is the next evolution in multi-sensor space-borne observations and synergistic data products. With an expected launch date in mid-2021, it aims to observe interactions among radiant energy transfer, clouds, aerosols and precipitation, so as to better understand controls on Earth's energy budget. The satellite is comprised of four instruments – the first spaceborne Doppler radar, a high spectral resolution lidar, a multispectral imager and a broad band radiometer. The novel features of the satellite include coincident measurements, higher radar sensitivity, Doppler capability and measured lidar ratio, thus providing an exciting opportunity to perform more accurate and informed analyses than before.

Atmospheric circulation models are a potential tool that we can use to evaluate our understanding of the features, processes, etc. that are observed by satellites. In anticipation of EarthCARE's launch and the advanced observations it will provide, we can begin to explore how this can be done using A-Train satellites, e.g. CloudSat and CALIPSO. In this study, we will also use the current simulations from Project DYAMOND (DYNAMics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains), which is a framework for intercomparing different atmospheric circulation models that are able to resolve atmospheric features and circulation at important scales. Our goal is to assess the similarities and discrepancies between the model and satellite observations, as well as the strengths and weaknesses of both, in order to determine how such work can be used in the future to enhance our use of the EarthCARE satellite.

#### Poster Session D / 258

### The relevance of different heterogeneous ice formation processes for the precipitation budget

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The efficiency of the known heterogeneous ice nucleation modes depends strongly on temperature and the properties of the available ice nucleating aerosol particles. E.g., at temperatures above -25°C

heterogeneous freezing occurs predominantly via the liquid phase (in layers of super-cooled liquid water) whereas at lower temperatures deposition or condensation freezing, or homogeneous freezing can take place, as well. Nevertheless, ice formation is required to form considerable amounts of precipitation via the so-called cold-rain process. Considering the large regional variability of aerosols, and thus of ice nucleating particles that leads to strong variability in the efficiency of heterogeneous ice formation processes, also the precipitation produced by certain freezing modes may vary by region.

The relationship between cloud top temperature (CTT) and the amount of precipitation reaching at ground level (RR) is investigated using data from the Cloudnet sites Leipzig, Germany (51°N), Limassol, Cyprus (33°N) and Barbados (13°N). A global analysis of the relationship between CTT and RR is accomplished based on observations of the Cloudsat satellite. At the coordinates around the Cloudnet stations cross-validation of the Cloudsat and Cloudnet datasets is performed. Global statistics of more than 10 years of observations with Cloudsat are presented together with multi-year observations at the Cloudnet sites.

First results obtained show, that for continental Europe and the Mediterranean only a fraction of approximately 1% of the total precipitation amount is clearly originating from warm-rain processes (e.g., drizzle). 40% of all precipitation is found to be initialized solely via liquid-dependent ice nucleation. About 15% may involve deposition or condensation freezing whereas the remaining 45% are possibly formed by homogeneous freezing. At tropical site Barbados, the warm-rain contribution to the total precipitation budget is found to be around 35%.

#### Poster Session D / 194

## Dependence of cloud ice and cloud-radiative effects on model resolution and model physics in regional ICON simulations of the NAWDEX campaign

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Cloud diabatic processes play an important role for North Atlantic weather systems. In particular, cloud-radiative effects are believed to have a large impact on cyclones and the large-scale circulation. In this study, we investigate the effects of model resolution and model physics on simulated cloud properties in regional ICON simulations for the NAWDEX field campaign.

The ICON simulations cover a large domain over the North Atlantic, and are conducted for horizontal resolution ranging from 80 km to 2 km. Furthermore, the cloud microphysical scheme is varied between a 1-moment scheme that predicts the mass of hydrometeors, and a 2-moment scheme that additionally predicts the number concentrations. For the higher resolutions, simulations with parameterized and explicit convection are performed.

For domain-mean cloud properties, total cloud-ice content and top-of-atmosphere longwave cloud-radiative effect are found do not strongly dependent on model resolution and the treatment of convection when the 1-moment microphysical scheme is used. In contrast, a strong sensitivity to resolution and convection is found for simulations with the 2-moment microphysical scheme. These difference in the domain-mean quantities for the 2-moment scheme are found to be related to an enhanced frequency of values of total cloud-ice content around 1 kg/m<sup>2</sup>, and an enhanced frequency of top-of-atmosphere longwave cloud-radiative effect with values around 120 W/m<sup>2</sup>. The changes in frequency are also found when the simulations are remapped to the same 1 deg x 1 deg latitude-longitude grid. Ongoing work is refining this analysis to focus on cirrus clouds of the warm conveyor belt region.

**Poster Session D / 174****UWLCM: a Modern LES Model with Lagrangian Microphysics**Piotr Dziekan<sup>1</sup> ; Maciej Waruszewski<sup>2</sup> ; Hanna Pawlowska<sup>1</sup><sup>1</sup> *Institute of Geophysics, Faculty of Physics, University of Warsaw, Warsaw, Poland*<sup>2</sup> *Institute of Geophysics, University of Warsaw***Corresponding Author(s):** piotr.dziekan@fuw.edu.pl

We report development of a new LES model called the University of Warsaw Lagrangian Cloud Model (UWLCM). The model consists of an Eulerian dynamical core and Lagrangian microphysics scheme. The anelastic dynamical core uses the MPDATA advection scheme and the generalized conjugate residual solver for the pressure problem. Implementations of the advection scheme and of the pressure solver are taken from the libmpdata++ library. The Lagrangian microphysics is an implementation of the Super-droplet method taken from the libcloudph++ library. Methods for coupling of the Eulerian and Lagrangian components are presented, including spatial and temporal discretizations and sub-stepping algorithms. The coupling is optimized for maximum concurrency of computations of the Eulerian dynamical core, computed on CPUs, with computations of the Lagrangian microphysics, computed on GPUs.

UWLCM results are compared with reference results of 11 other LES models, which use either bin or bulk microphysics. The comparison is done on results of simulating a drizzling marine stratocumulus using the DYCOMS-RF02 setup. Time series and vertical profiles are found to be in general agreement with the reference models. Some discrepancies are found, which we attribute to the implicit LES approach used in UWLCM and to the use of a Lagrangian microphysics scheme.

Lagrangian microphysics scheme explicitly resolves microphysical processes, similarly to the bin microphysics. Therefore a more detailed comparison with results of the bin models is presented. Advantages of Lagrangian microphysics are discussed: lack of numerical diffusion in the size spectrum and explicit modeling of droplet activation.

**Poster Session D / 216****Study of droplet-size distribution in turbulent clouds using stochastic microphysics at unresolved scales**Gustavo Abade<sup>1</sup> ; Wojciech Grabowski<sup>2</sup> ; Hanna Pawlowska<sup>3</sup><sup>1</sup> *Institute of Geophysics, Faculty of Physics, University of Warsaw*<sup>2</sup> *National Center for Atmospheric Research*<sup>3</sup> *Institute of Geophysics, Faculty of Physics, University of Warsaw***Corresponding Author(s):** gustavo.abade@fuw.edu.pl

We study the evolution of the droplet-size distribution under the influence of turbulence fluctuations at subgrid scales (SGS). The microphysics is forced by a synthetic, turbulent-like flow that mimics a stratocumulus topped boundary layer (STBL) as in Pinsky *et al.* (2008). Cloud droplets and unactivated cloud condensation nuclei (CCN) are described by Lagrangian particles (superdroplets). Collisions and coalescence of droplets are not considered. In this framework, the cloud microphysical properties are shaped in part by the interaction of the cloud with the overlaying and underlaying unsaturated layers. Unactivated CCN enter the cloud layer from below and from the dry overlaying inversion layer due to entrainment. The synthetic STBL flow is constructed as a superposition of random Fourier modes, where the turbulence resolution length scale is a controlling parameter. However, a resolution that is sufficiently fine to represent the smallest eddies is not feasible. The processes occurring in the range of unresolved scales (e.g., the transport of cloud particles, supersaturation fluctuations, turbulent mixing, and the resulting stochastic droplet activation and growth by condensation) are modeled using a Monte Carlo scheme. In the stochastic picture of the SGS microphysics, supersaturation fluctuations drive a “random walk” of the droplet radii in the Köhler potential landscape set by the local resolved supersaturation. It is shown that SGS turbulence plays

a key role in broadening the droplet-size distribution towards larger sizes. Also, the feedback on vapor of stochastically activated droplets buffers the variations of the mean supersaturation driven by updrafts and downdrafts. This extends the distance over which entrained CNN are activated inside the cloudy layer and produces multimodal droplet-size distributions.

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### Poster Session D / 233

## Observing the Relationship between Large-Scale Vertical Motion and Cloud Structure in the Maritime Tropics

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Investigations in understanding clouds and convection developed independently from those aimed at understanding large-scale circulations, primarily because of limitations in observational capability and computing power. The limitations in calculating large-scale divergence can be overcome using new measurement techniques which infer the horizontal divergence from distributed dropsondes. We study the relationship between clouds and vertical atmospheric circulation in the mesoscale, by employing the regression method to measurements from distributed dropsondes. To achieve this, observations from the circular flight patterns performed as part of the second *Next-Generation Aircraft Remote Sensing for Validation Studies* (NARVAL2) campaign are used. The campaign took place upwind of Barbados (13° N, 59° W), over the tropical north Atlantic, in August, 2016. Dropsondes launched along these circles measured horizontal wind properties, which were used to determine vertical profiles of divergence, vorticity as well as vertical wind velocity, thus providing information about the vertical circulation in that region (circles of ~150 km diameter). The conditions present for these circles are distinguished on the basis of thermodynamic parameters such as integrated water vapour, moist static energy, lower tropospheric stability and dynamic parameters such as horizontal wind direction, divergence, vorticity and vertical wind velocity. The circles are studied on a case-by-case basis, and using the divergence values, budgets for heat, mass and moisture are constructed for the regions. The measurements sample regions where integrated water vapor varies from ~30 to ~60 mm, lower tropospheric stability across ten regions for which circles constraint divergence varies from ~11 to ~19 K and vertical motion varies from strongly subsiding to strongly convergent in regions that cross the ITCZ. These conditions are then associated with the cloudiness in the region, investigated using the airborne radar measurements as well as satellite observations, which give a clearer picture of the large scale environment as well. Detailed analyses suggest the extent to which the large-scale environment influences the amount and organisation of clouds. These investigations into how the measured divergence influences the cloud amount and organisation in a region, would be a novel approach to understanding the interplay between clouds and circulation, as it fills the gap of information relating large-scale vertical motion with clouds.

### Poster Session D / 241

## Recent developments in the Canadian 2.5 km NWP model: from convection parameterization to explicit connection between the P3 microphysics and the radiation transfer scheme

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The Canadian High Resolution Deterministic Prediction System (HRDPS, Milbrandt et al 2016) is the official NWP guidance for 0-48h forecasts across Canada. It has an horizontal resolution of 2.5 km.

The HRDPS is piloted by its lateral boundaries by the 10 km Regional Deterministic Prediction System (RDPS) which is also piloted by the 15 km Global Deterministic Prediction System (GDPS). All these models are becoming more and more seamless in their physical parameterizations. All three models are using the same updated planetary boundary layer moistTKE scheme (Belair et al 2005), a shallow convection parameterization inspired by Bechtold et al (2001) and an updated version of the Kain Fritsch (1990,1993) deep convection parameterization, as well as the same radiative transfer (RT) scheme (Li and Barker 2005).

Regarding the deep convection parameterization, adjustments were made to the different parameters to adjust its application to the high resolution of the HRDPS. In contrast to the RDPS and GDPS, the Kain Fritsch (KF) scheme for the HRDPS is mainly use as a trigger in conditions of high CAPE (when the model resolved vertical motion is not enough to activate the microphysics condensation). Then, by its detrainment of cloud condensate to the microphysics scheme it allows the later to take the relay, and the KF scheme only contributes to the early phase of the deep convective events, with a contribution of approximately only 15% of total precipitation. It have been shown in different versions of the HRDPS that the use of the adjusted KF improves significantly the summer precipitation forecasts across Canada and Northern USA.

The major aspect of the HRDPS that differs from the lower resolution models is the microphysics scheme P3 (Morrison and Milbrandt 2015) and its new explicit connection to the RT scheme (through the effective radii of liquid and ice clouds). This new connection and the redefinition of "clouds" seen by the RT scheme have statistically significant impacts on the model, particularly for surface temperature.

Results from case studies and surface skill scores for 48 h hindcasts over two months for winter and summer seasons will be presented. It will be shown how the Kain Fritsch parameterization adapted for 2.5 km can improve the timing, intensity and structure of summer precipitation, and how the microphysics-radiation interface has different impacts on surface temperature depending on season.

**Poster Session D / 248**

### **3D Cloud Microphysics Derived by a Combination of the Hyperspectral Imaging Spectrometer specMACS and Active Remote Sensing Instruments**

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Clouds are one of the largest uncertainty factors in climate models and influence local and global weather forecasts. Forecast errors arise when macro- and microphysical cloud properties are not adequately parameterized in weather or climate models. Remote sensing of 3D cloud micro- and macrophysics leads to a better understanding of subgrid scale cloud processes and parameterizations can be improved. The observations also can be used to constrain model predictions. Both will lead to a further reduction in climate and weather prediction errors.

The retrieval of 3D cloud micro- and macrophysics can be achieved by combining active with passive remote sensing instruments: Spectral imagery from a research aircraft forms the basis to combine information from lidar, radar, and microwave radiometer. The steps are: Firstly, passive hyperspectral specMACS measurements have a wider swath and higher resolution compared to active remote sensing methods. Secondly, a nadir pixel is identified for each non-nadir pixel where infrared specMACS spectra match (approach of Barker et al., 2011). Thirdly, vertical information from active sensors is distributed onto non-nadir pixels. Thus, active and passive remote sensing methods can be combined.

The hyperspectral imaging spectrometer specMACS alone allows the determination of horizontal 2D information such as cloud size, cloud distribution, optical thickness, stereographic cloud top height, effective radius and thermodynamic phase. The combination with active remote sensing measurements, e.g. Liquid Water Path from microwave radiometers or Cloud Top Height from lidar measurements, creates new possibilities: A more advanced effective radius retrieval as well as a new cloud droplet number concentration retrieval is possible. Additionally, information about the entrainment strength can be gained.

Cloud 3D reconstructions will be presented for the first cases. The final aim is to quantify the effect of diabatic heating and cooling of these 3D clouds.

**Poster Session D / 93**

## The dependency of Ekman pumping on turbulence

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Friction by boundary-layer turbulence has an impact on the large-scale flow properties. In this study we will argue that the magnitude of Ekman pumping (large-scale vertical velocity) has a distinct maximum value. We confine our analysis to steady-state conditions and we use a bulk, linear parameterization for the momentum flux. We present new diagnostic relations for the large-scale divergence of horizontal wind (*Div*) and the large-scale vertical velocity. For a pure frictionless geostrophic flow the large-scale divergence of horizontal wind is zero. The presence of boundary-layer turbulence act as a drag on the flow that generates an ageostrophic flow, which, in turn, drives a small large-scale velocity, the so-called Ekman pumping. The key conclusions are as follows. In the limit of infinite turbulent friction the horizontal wind will tend to zero, and consequently  $Div \rightarrow 0$ . This notion suggests a maximum effect of turbulent friction on the magnitude of *Div*. More precisely, *Div* is found to depend on the curl of the geostrophic wind, or equivalently on the Laplacian of the pressure field, in addition to a function  $F$  that depends on a non-dimensional friction factor.

**Poster Session D / 265**

## Structure of the inter-cloud atmosphere in a case of tropical deep convection

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Entraining cloud (or plume) models constitute an important part of many convection parameterizations implemented in operational atmospheric models. For instance, the Plant-Craig stochastic scheme, as implemented in ICON 1, employs the Kain-Fritsch plume model [2].

In most cloud models, air parcels, whose properties are derived from the host model local solution, are launched either near the surface or near cloud base. These parcels are then lifted through a mean atmosphere, also taken from the host model solution, and the vertical distribution of mass flux is then calculated along each parcel trajectory. This situation is obviously not representative of a real atmosphere in which individual parcels would encounter different thermodynamic conditions during their ascent. This is especially true as sub-grid scale fluctuations of temperature and moisture are generally not considered when calculating the parcels properties. This is this particular aspect of convection parameterizations that we wish here to improve by studying the detailed structure of the inter-cloud atmosphere in high-resolution simulations.

We propose here to use idealized Cloud Resolving Model (CRM) simulations of tropical convection at a horizontal resolution  $\sim 100$  m to analyze the structure of the inter-cloud troposphere, and correlate the development of new convective cells with particular properties thereof (eg. moisture and temperature fluctuations). Four numerical experiments are designed for this study, each representative of a case of shallow to deep convection transition in the tropics, but with different initial moisture profiles (all other settings being equal), similar to [3]. As radiative fluxes are held constant throughout the simulations, the shallow cumuli that form shortly after initialization quickly transition to deep precipitating clouds which are then maintained in a slowly evolving state. At this stage, it is possible to draw statistics (global and conditioned on cloud sizes) of the inter-cloud troposphere, most notably first contact distributions characterizing the dimensionality of the inter-cloud region. In addition, one can also correlate fluctuations of thermodynamic quantities (potential temperature, virtual potential temperature, water vapor mixing ratio...) to the distance to the nearest clouds (spatial correlations), as well as to the prior and future presence of clouds (temporal correlations). The analyses conducted here should eventually lead to a more precise representation of the atmosphere through entraining parcels ascend in 1D plume models.

**Poster Session D / 296**

## **On the spatiotemporal variability of clouds, and its consequences for radiative closure studies and the accuracy of solar surface irradiance retrievals**

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Over the past decades, reliable algorithms have been established for retrieving cloud properties and radiative fluxes from multispectral satellite images. These products are nowadays used in applications ranging from climate and weather research to nowcasting of energy production by solar power plants. The accuracy of retrieved solar surface irradiance is commonly assessed using high-quality ground-based observations as reference. Due to the high variability of clouds and the solar radiation, large deviations occur frequently on an instantaneous basis. Thus, sufficiently long periods are commonly used for validation studies in order to quantify random and systematic uncertainties. This averaging however also restricts our ability to test radiative closure on a case-by-case basis. Several physical mechanisms limit the instantaneous correlation of ground-based and satellite observations: while satellite products correspond to a spatial area given by the pixel resolution, ground-based observations are point measurements with limited representativeness for extended spatial domains. The effects of 3D radiative transfer and horizontal photon transport cause a decorrelation of the solar irradiance at the top and bottom of the atmosphere. In addition, cloud variability and thus the uncertainty depends strongly on cloud type and synoptic conditions. A better understanding of

these effects is highly desirable to advance our understanding of cloud-radiation interactions, and to assess radiative closure in cloudy conditions. In the present study, solar surface irradiance as retrieved from METEOSAT SEVIRI's rapid scan service with a 5-minute repeat cycle are compared to a unique dataset of spatially resolved solar surface irradiance measured by a dense network of 99 autonomous pyranometers, which was operated across a 10x10km<sup>2</sup> domain during the HOPE field campaign from April-July 2013. A cloud-type classification is applied to group uncertainties according to synoptic conditions, and a wavelet-based multi-resolution analysis is used to compare the power spectra of both datasets. The benefits from a novel cloud and irradiance retrieval utilizing SEVIRI's high-resolution visible channel at a 1x1km<sup>2</sup> nadir pixel resolution are evaluated versus standard resolution 3x3km<sup>2</sup> products. Using the optimum averaging technique and exploiting the dense spatial coverage of pyranometer observations, the comparison with individual stations is contrasted to that with extended spatial domains. Finally, conclusions are drawn for the feasibility of a field campaign for testing column radiative closure based on the EarthCARE satellite mission, and for the expected increase in accuracy of products for the upcoming Meteosat Third Generation.

Poster Session D / 306

## Using machine learning to identify regimes of convective organisation in satellite images

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The precise mechanisms driving different forms of convective organisation which arise both in nature and in simulations are currently unknown. With a tool to automatically classify regions into distinct forms of convective organisation it will be possible to produce a statistical description of the most likely large-scale and local environmental conditions (e.g. windshear, horizontal convergence) present in differently organised states. Using inductive learning with partially labelled GOES-R and MODIS imagery, a machine learning model has been developed to classify regimes of convective organisation in satellite imagery. First results will be presented producing a map of the distribution of different forms of convective organisation, with the aim to later link these to the large-scale forcing and local conditions.

Poster Session D / 107

## Understanding mesoscale organization of closed-cell marine stratocumulus using large-eddy simulation and observations from the ARM Eastern North Atlantic Site

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This study investigates the mechanisms that promote mesoscale closed cellular organization in well-mixed non-drizzling stratocumulus-topped marine boundary layers using large-eddy simulation (LES) over an approximately 60x60 km<sup>2</sup> periodic domain. Simulations show that the mesoscale closed-cell stratocumulus organization is driven by positive feedback from cloud-induced mesoscale perturbations of longwave radiative cooling. A conceptual model for closed-cell stratocumulus as a mesoscale wavelength hydrodynamic instability in which mesoscale moist and dry anomalies spontaneously grow is presented. The governing role of humidity anomalies in promoting mesoscale cloud variability is confirmed via the observations at the Eastern North Atlantic Site operated by the US Department of Energy Atmospheric Radiation Measurement (ARM) program. In LES simulations in which long-wavelength sinusoidal moisture anomalies are initially imposed,

these anomalies evolve into amplifying closed cells. The cell structure is visualized with a compositing approach based on sorting grid columns by their mesoscale-smoothed total water path. A thermally direct mesoscale circulation pattern develops in the interior of the boundary layer with buoyant mesoscale updrafts, thicker cloud, and a slightly higher capping inversion in the moister columns. There is a mesoscale flow of above-inversion air down the slightly sloping capping inversion from the moist to the dry regions, reinforced by cloud-top radiative cooling. This strengthens the mesoscale anomalies by preferentially cooling and drying the already dry regions. The sloping inversion flow is not driven as efficiently if the radiative cooling is artificially horizontally homogenized, partly disrupting this positive feedback and the resulting closed cell development.

**Afternoon session: Topic V / 60**

## **Aerosol Impact on Warm Rain Initiation in Turbulent Clouds Using Direct Numerical Simulation (DNS)**

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This work studies the fundamental processes of aerosol-cloud interaction to explore the impact of turbulence and hygroscopic seeding on warm-rain initiation. Aerosol activation, droplet condensation, and collisions are integrated into the DNS model. Cloud particles grow by condensation and collision in a turbulent, supersaturated environment. The DNS model employs Lagrangian microphysics and Eulerian dynamics to accurately calculate the evolution of the droplet size distribution (DSD) under the impact of the mean-state updraft imposed onto the entire domain and local-scale fluctuation induced from microscale thermodynamics (droplet condensation) and dynamics (turbulence and droplet hydrodynamic interaction).

We conducted 32 simulations with various aerosol conditions and different turbulent environments. In this presentation, a detailed comparison among the simulations is made to investigate the contribution of turbulence, hygroscopicity, and aerosol loading (by changing the size spectrum and number concentration) to the droplet growth and the broadening of droplet size distribution.

**Afternoon session: Topic V / 37**

## **The particle-based microphysical model McSnow**

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Storm resolving simulations possess lower uncertainties as they resolve several physical processes explicitly that need to be parametrized otherwise, for instance convection. However, the remaining parametrized small-scale processes such as cloud microphysics then become more important as, e.g., they need to provide the correct heating rates for convective events.

We developed a novel “microphysics resolving” model, the Monte-Carlo microphysics model McSnow1, to better understand the interaction of the microphysical processes sedimentation, aggregation, riming, ice multiplication, vapor diffusion, melting, shedding and breakup. Within this super-particle model, for each individual particle the ice mass, rime mass, rime volume, number

of monomers and liquid mass is predicted establishing a five-dimensional particle size distribution. While being computationally more efficient than a corresponding high-dimensional bin model, this approach also enables to look at the growth history of individual precipitation particles. Compared to current mostly one-dimensional bin microphysics models, McSnow provides a more consistent description of complex hydrometeors as it, for example, tracks the rime density for each super-particle.

With semi-idealized sounding-based one-dimensional McSnow simulations we show that the Monte-Carlo method provides a feasible approach to tackle this complex problem. Additionally, McSnow is integrated into the non-hydrostatic model ICON-LEM building on an online Lagrangian trajectory model and thus can also be run for three-dimensional, highly dynamic cases. We run simulations of idealized deep convective events with hundreds of million McSnow super-particles representing the microphysics. We analyze these simulations to gain an in-depth understanding of the microphysical processes and aim to improve their parametrizations in numerical weather prediction and climate models.

1 S. Brdar and A. Seifert 2017, McSnow – A Monte-Carlo particle model for riming and aggregation of ice particles in a multidimensional microphysical phase space, *Journal of Advances in Modeling Earth Systems* 10, 10.1002/2017MS001167

**Afternoon session: Topic V / 199**

## **Understanding the Zonal Variability of Thermodynamic Feedbacks in the Tropics: Global Storm-resolving Models versus Observations**

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Recent planetary-scale storm-resolving models, run for weather forecasting and climate prediction purposes, resolve the energy transfer between the convective scale (10 km) and the large-scale circulation (10,000 km). The goal of storm-resolving modeling is to improve the accuracy of this multi-scale energy transfer, yet there are no simple metrics to evaluate it in both models and observations of the atmosphere. We focus on the zonal variability of precipitable water in the Tropics because of its importance for energy transport and climate sensitivity. We quantify how radiative and surface enthalpy fluxes contribute to this variability at each scale by addressing the following questions:

What are the preferential scales of variability from radiative and surface energy fluxes in models and observations? Can we use the differences between models and observations to identify radiative and convective biases which can be improved in the next generation of global storm-resolving models?

We use a spectral moist static energy budget and leverage the weak temperature gradient approximation to relate the zonal variability of precipitable water to the net radiative and surface enthalpy fluxes. We compare these scale-by-scale variance rates in four different types of convection-resolving models - elongated-domain cloud-permitting model, super-parametrized climate model, aquaplanet cloud-permitting model, and Earth-like cloud-permitting model with realistic rotation and land mass - to the scale-by-scale variance rates calculated from satellite observations and meteorological reanalysis products. By adopting wavelet instead of Fourier spectral analysis, we can also isolate specific regions of the globe for more targeted comparisons, e.g. observations over the Pacific basin versus models in aquaplanet configuration.

Compared to observations, aquaplanet models capture the variance injected by radiative fluxes and removed by surface enthalpy fluxes above the  $\sim 1000$  km scale, even when run on smaller domains (e.g. 10,000 km long). Land-sea thermodynamic contrasts add variance at the largest scale ( $\sim 40,000$  km) through longwave and surface enthalpy fluxes, while removing variance through shortwave radiation. Models typically underestimate variability at the zonal scale of  $\sim 10,000$  km by underestimating longwave coherence (high-cloud bias) and overestimating the destruction of variance by surface enthalpy fluxes.

Our spectral framework allows the comparison of models to observational products across configurations and resolutions, from the convective to the planetary scale. Understanding the preferential scale of zonal variability in observations can help decrease the biases in weather prediction and climate sensitivity in the Tropics through refinement of cloud processes, or simply tuning of atmospheric water zonal spectra to observations.

**Afternoon session: Topic V / 113**

## **Influence of turbulent temperature and saturation fluctuations on droplet activation**

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Atmospheric clouds are highly non-stationary, inhomogeneous, and intermittent, and embody an enormous range of spatial and temporal scales. Strong couplings across those scales between turbulent fluid dynamics and microphysical processes are integral to cloud evolution (Bodenschatz et al., 2010).

Besides clouds being highly complex systems in themselves, they occur sporadically in locations usually hard to reach. Therefore, investigating atmospheric clouds in-situ is an ambitious, expensive and often impossible task. To make things even worse, measurements in atmospheric clouds suffer from a lack of reproducibility regarding initial and boundary conditions. Due to these issues, the examination of individual cloud processes in the laboratory is mandatory for increasing our understanding of cloud microphysical processes, and their interactions with turbulence (Stratmann et al., 2009).

The turbulent moist air wind tunnel LACIS-T (Turbulent Leipzig Aerosol Cloud Interaction Simulator) is an ideal facility for pursuing mechanistic understanding concerning these processes and interactions under well-defined and reproducible laboratory conditions. Within LACIS-T, we are able to precisely adjust turbulent temperature and water vapor fields, so as to achieve supersaturation levels allowing for, e.g., the detailed investigation of aerosol particle activation to cloud droplets. LACIS-T is a closed loop wind-tunnel. The actual measuring section of the tunnel is 2 m long, 80 cm wide and 20 cm deep. Cloud formation occurs via turbulent mixing of three conditioned flows (i.e. two particle-free air streams, and one aerosol stream), and is initiated at the inlet of the measuring section. The turbulence is generated by two passive planar grids in the air streams. The air streams are humidified by Nafion humidifiers and tempered by two separate heat exchangers. The aerosol flow is introduced into the mixing zone of the two air streams. In the measuring section, the characterization of the respective fluid and thermodynamic states, as well as the microphysical properties of the cloud formed (e.g., droplet size and number), is carried out. After passing through the measuring section, the entire flow is dried, split up again into two streams driven by blowers and cleaned by filters.

Here we will introduce LACIS-T as a device for investigating aerosol cloud interactions under turbulent conditions. Specifically, we will deal with the activation behavior of size-segregated sodium chloride particles. We will present first evidence concerning the effects of turbulence on cloud droplet activation.

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**Afternoon session: Topic V / 79**

## **Modeling of cloud microphysics: Can we do better?**

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Representation of cloud microphysics is a key aspect of simulating clouds. From the early days of cloud modeling, numerical models have relied on an Eulerian approach for all cloud variables, not only for temperature and water vapor, but also for cloud condensate and precipitation. Over time the sophistication of microphysics schemes has steadily increased, from simple single-moment bulk warm-rain schemes, through double- and triple-moment bulk warm-rain and ice schemes, to complex bin (spectral) schemes that predict the evolution of cloud and precipitation particle size distributions. As computational resources grow, there is a clear trend toward wider use of bin schemes, including their use as benchmarks to develop and test simplified bulk schemes. We argue that continuing on this path brings fundamental challenges difficult to overcome. This is because of the complexity of processes involved (especially for ice), the multiscale nature of cloud-scale flows that Eulerian approaches are not able to cope with, conceptual issues with the Smoluchowski equation that is solved by bin schemes to predict evolution of the particle size distributions, and numerical problems when applying bin schemes in multidimensional cloud simulations. The Lagrangian particle-based probabilistic approach is a practical alternative in which the myriad of cloud and precipitation particles present in a natural cloud is represented by a judiciously selected ensemble of point particles called super-droplets or super-particles. Advantages of the Lagrangian particle-based approach when compared to the Eulerian bin methodology will be discussed and illustrated with computational examples. Prospects of applying the Lagrangian particle-based approach to more comprehensive simulations involving clouds, for instance targeting deep convection or frontal cloud systems, will be discussed.

**Afternoon session: Topic V / 229**

## **The impacts of CCN concentration, updraft speed, and turbulence enhancement of droplet coalescence on the development of raindrops**

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A long-standing scientific challenge has been explaining the observed short time between initial cloud droplet formation and the development of raindrops in warm (liquid-water-only) cumulus clouds. Cloud droplets initially grow by condensation, but this process by itself is too slow to produce raindrops in the observed short times. Growth by collision and coalescence in nonturbulent air is rapid enough to do so once cloud droplets grow to a diameter of about 0.1 mm. How cloud droplets grow to this size in a short time has been the puzzle. During the last two decades, scientists have recognized that turbulence can accelerate droplet growth by collision and coalescence, but quantifying its impact has been theoretically difficult and computationally expensive.

Krueger and Kerstein (2018, doi: 10.1029/2017MS001240) developed a new, economical, and accurate method to simulate droplet growth by collision and coalescence in turbulent air. A simplified, yet physically based, representation of the smallest turbulent eddies—which predominantly influence

droplet collision rates—and their interactions with droplet motions is the basis of the method, which captures the enhancement of collision rates due to the subtle phenomenon of turbulence-induced droplet clustering. The method gives excellent agreement with DNS of coalescence growth of sedimenting droplets for turbulence levels typical of cumulus clouds. Results demonstrate that rain formation can be significantly accelerated by turbulence enhancement of collision rates.

We are currently examining the relative roles of CCN concentration, updraft speed, and turbulence enhancement of droplet collisions and coalescence on the development of raindrops in updrafts using a new version of ClusColl that includes droplet growth by condensation. Chen et al. (2018, doi: acp-18-7251-2018) showed that the narrowing of droplet size distributions by condensational growth increases the effects of turbulence enhancement of coalescence growth compared to simulations without condensation. Her results suggest the intriguing possibility that turbulence combined with condensation may allow significant coalescence growth to occur even in the presence of large CCN concentrations.

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## Scientific wrap-up of the day

Morning session: Topic I / 162

### Toward reduction of the uncertainties in simulations of clouds and precipitation using Nonhydrostatic Icosahedral Atmospheric Model (NICAM)

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In estimates of climate sensitivity obtained from global models, the need to represent clouds introduces a great deal of uncertainty. To address this issue, approaches using a high-resolution global non-hydrostatic model are promising: the model captures cloud structure by explicitly simulating meso-scale convective systems, and the results compare reasonably well with satellite observations. We review the outcomes of the recent studies aimed at reducing the uncertainty in climate models due to cloud processes using a global non-hydrostatic model (Satoh et al. 2018). In our studies, we use the non-hydrostatic icosahedral atmospheric model (NICAM) to study cloud processes related to climate change. NICAM performs numerical simulations with much higher resolution (about 3.5, 7, or 14 km mesh) than conventional global climate models (GCMs) using cloud microphysics schemes without a cumulus parameterization scheme, which causes uncertainties in climate projection. We mainly had three research targets: analyzing cloud changes in global warming simulations with NICAM with the time-slice approach; sensitivity of the results to the cloud microphysics scheme employed; and evaluating circulation changes due to global warming. We had implemented a double-moment bulk cloud microphysics scheme and evaluated its results using satellite observation and large-eddy simulations, as well as comparing it with a bin cloud microphysics scheme. The future projection simulations show in general increase in high cloud coverage, contrary to results with other GCMs. Changes in cloud horizontal-size distribution size and structures of tropical/extratropical cyclones can be discussed with high resolution simulations. As highlights of recent studies, we also describe results from the coordinated program called DYAMOND and RCEMIP (Wing et al. 2018; Ohno and Satoh 2018).

References:

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**Morning session: Topic I / 249**

## Hic Sunt Dracones

Daniel Klocke<sup>1</sup> ; Team DYAMOND<sup>2</sup>

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Global storm-resolving simulations are performed by an increasing number of modeling groups. The DYAMOND (DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains) is the first project to inter-compare how such models represent the multi-scale structure and their interactions in the atmosphere, with a particular focus on precipitation, clouds and large-scale circulations. Eight modeling groups run their models from the same initial conditions for a period of 40 days with prescribed time-varying sea-surface temperature.

The explicit representation of convection allows updrafts to dynamical interact with their environment. The resolved storm-scales interact with the meso-scale and impact the large-scale circulation. The hope from global storm-resolving climate models is, that some long-standing atmospheric model biases related to the representation of deep convection will simply disappear. If this hope is founded will be explore in the DYAMOND ensemble and where the new sources for differences in this class of simulations are lying.

**Morning session: Topic I / 140**

## Tropical cyclones and convectively-coupled equatorial waves in global cloud-resolving simulations

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One of the greatest challenges in simulating the global atmosphere is modeling tropical convection. Past generations of global models could not resolve tropical convection and required cumulus parameterization schemes to account for convective processes. It is well known that these parameterization schemes are one of the biggest sources of error in atmosphere models and hamper the prediction of societally relevant tropical weather phenomena such as tropical cyclones and convectively-coupled equatorial waves. To alleviate the problems stemming from parameterized convection, scientists are beginning to use global cloud-resolving models, i.e., global models with resolution high enough to make cumulus parameterization obsolete. These models are often heralded as game changers in simulating atmospheric phenomena, a hypothesis that is tested in this study by analyzing several global cloud-resolving simulations in terms of tropical cyclones and convectively-coupled equatorial waves. The simulations were produced with the Model for Prediction Across Scales (MPAS) using grid spacings of 3.75 and 4 km (the 3.75 km simulation is the MPAS contribution to the DYAMOND project). Overall, the evaluation demonstrates that global cloud-resolving models are an important

step towards improved weather and climate predictions. The simulations capture the essential characteristics of tropical rainfall and show promise to be a “one stop shop” for tropical cyclone track and intensity predictions. Furthermore, the propagation of convectively-coupled equatorial waves is simulated much more realistically compared to models with cumulus parameterization. On the other hand, the cloud-resolving MPAS simulations suffer from some notable biases. In particular, they produce too many and too intense tropical cyclones. These biases need to be improved to make global cloud-resolving models a prime tool for simulating the tropical atmosphere, a point that is especially important with global cloud-resolving climate simulations on the horizon.

**Morning session: Topic I / 42**

## **Detection and attribution of cloud and precipitation adjustments to aerosol perturbations**

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Although aerosols are a key factor for atmospheric water vapor to condensate and form clouds, the aerosol-cloud interactions continue to be a challenge for climate models. Therefore, it is crucial to study how changes in atmospheric aerosol concentration affect clouds and precipitation, either in terms of type, intensity, quantity, time duration or delay in formation. Moreover, changes in aerosol burden also have an effect to cloud microphysical properties, with more aerosol load the smaller the cloud droplets become. Ultimately, cloud adjustments to anthropogenic aerosol perturbations remain an important source of uncertainties on current radiative forcing estimates.

To study the adjustments of clouds and precipitation to aerosol perturbations a set of highly resolved simulations (165 m) with the ICOSahedral Non-hydrostatic Large Eddy Model (ICON-LEM) have been performed over Germany with the Cloud Condensation Nuclei (CCN) concentrations of the 2nd of May 2013, as control simulation, and with 1985 CCN concentration profiles (i.e. peak of pollution in Europe), as perturbed simulation. Thanks to the fact that the cloud resolving ICON-LEM model has an advanced two-moment mixed-phase bulk micro-physical parametrization scheme, the effects can be investigated by the analysis of the number concentration and specific content profiles of five hydrometeors, as well as for the integrated spatial distributed variables and macroscopic characteristics.

Preliminary results show increased LWP, and more and smaller cloud droplets which produce significant increase in cloud albedo, since changes in the solar radiation at the TOA are detected. Although negligible changes are found in surface rain rate domain average (c.a. 0.18%), with smaller cloud particles the collision-coalescence should be reduced, and actually, a change in the domain mean rain pattern is found since the rain peak around 17h is slightly reduced and more rain is precipitated in the perturbed simulation between 18 to 20h in comparison to control simulation. Cloud phase effects concerning mixed-phase and ice clouds are also investigated since smaller cloud droplets may delay the onset of freezing. Finally, regarding the vertical extent effects, slightly thicker clouds, and slightly higher cloud tops and bases are found.

**Morning session: Topic I / 177**

## **Evaluating convective storm characteristics against radar observations around the world**

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Several statistical approaches for evaluating convective storms were developed in the DYMECS project using radar observations in southern England and have been further developed for use with radar data from other providers. Here, we present results evaluating four summer months of 1.5-km forecast simulations from the South Africa Weather Service (SAWS), run with the Met Office Unified Model, against the SAWS operational radar network. The forecasts typically initiate convection at the same time of day, around noon, with convective storms growing into mesoscale systems by the early evening. The observations indicate a much broader timeframe of initiation and a diverse range of storm sizes at all times.

The long evaluation period highlights several potential challenges for global convection-permitting simulations. Firstly, the simulations represent convective storm characteristics such as size and duration better in February, when tropical influences dominate in southern Africa, than in November, when the mid-troposphere is colder and mid-latitude disturbances are more frequent. Secondly, for case studies in November, we find little improvement when increasing resolution from 4 km to 1.5 km or even 300 m, which is likely because the dominant storm sizes are of scales that are well-represented at 4-km grid length. This is in sharp contrast with results from southern England, where a grid length of 200 m was required for an adequate physical representation of convective storms. Both these findings, regarding the seasonal differences and regional differences in convective storm characteristics, support the development of scale-aware parameterization schemes.

Our findings also demonstrate the need for developing global verification approaches to convection-permitting models. Through the Met Office Unified Model Partnership, we are aiming to pursue these radar-based evaluation techniques to allow the model physics to be challenged in various well-observed regions around the world on a routine basis.

**Afternoon session: Topic I / 214**

## Climate Modeling in 2030

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Currently major efforts are underway towards refining the horizontal grid spacing of climate models to about 1 km, either by increasing the resolution of current GCMs, or by extending the computational domain of high-resolution RCMs. There is well-founded hope that this increase in resolution represents a quantum jump, as it enables replacing the parameterizations of moist convection and gravity-wave drag by explicit treatments. It is expected that this will improve the simulation of the water cycle and extreme events, and reduce uncertainties in climate projections. However, the development of such modeling strategies requires a concerted effort.

Here we report about the Swiss crCLIM initiative to investigate some of the key scientific and technical challenges associated with such an undertaking. The presentation is largely based on a paper that is currently in preparation (see reference below).

In exploring high-resolution climate modeling, we utilize an RCM that is able to conduct decade-long continental-scale simulations at 2 km resolution. We argue that the key challenges are similar as those with a GCM. The model employed is a version of the COSMO model that runs entirely on graphics processing units (GPUs). Examples will highlight the prospects and key challenges. It is demonstrated that horizontal resolutions around 1 km enable the credible simulation of many mesoscale phenomena. Although cloud structures are not yet fully resolved, studies suggest that in a bulk sense there is convergence at grid resolutions around 2 km, i.e. the respective feedbacks with the larger-scale flow are approximately captured.

It is argued that the output avalanche of high-resolution simulations will make it impractical or impossible to store and analyze the data. Rather, repeating the simulation and conducting online analysis may become more efficient. A prototype system of this type will be presented. The ultimate goal is to develop a binary-reproducible simulation system that ensures reproducibility across hardware architectures, in conjunction with a data virtualization layer as a common interface for output analyses. An assessment will be provided of the potential of these novel approaches. These considerations suggest that workflows for maintaining models and conducting high-resolution simulations may fundamentally change in the next decade.

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**Afternoon session: Topic I / 206**

## **On the confluence of cloud parametrization from cloud-scale models and global modelling systems**

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“Eventually, all things merge into one, and a river runs through it” (Norman Maclean, 1976).

There is a rich history of development of detailed parametrizations of cloud and precipitation processes based on pioneering observations and theoretical studies through the 20th Century and continuing to this day. This has led to a range of complexities of microphysics parametrizations that have been implemented in cloud-scale resolving models to study detailed processes relating to cloud, turbulent flows, convection and precipitation.

Global numerical weather prediction (NWP) and climate model development has progressed from the other end of the model resolution spectrum, where typical grid sizes of order 100km have meant that the representation of cloud microphysical processes are highly approximated, because the parametrization of the unresolved variability of the dynamical motions (e.g. deep convection) dominates the uncertainty.

However, advances in computing power are allowing global model resolution to continue to increase towards the storm-scale (resolutions of order 1 km) and current limited area models for research and operational NWP, already at this scale, are expanding their domains.

What does this mean for model cloud and precipitation parametrization development? As the sub-grid variability assumptions become less important with higher resolution and turbulent motions become increasingly resolved, the formulation of the microphysics becomes more important. But are the microphysics schemes in current storm-scale models appropriate for the full range of global meteorological regimes and subtle interactions with the global circulation? Is increasing the complexity of current global model microphysics necessary, or a distraction? Can we have one merged

cloud and precipitation parametrization scheme that works for all resolutions of the model - following the concept of a seamless modelling system - or will we continue to need different schemes for different resolutions?

I will use examples from the ECMWF global NWP model to discuss these questions and indicate directions of cloud and precipitation parametrization development in global models for the future.

**Afternoon session: Topic I / 154**

## **Global System for Atmospheric Modeling (GSAM): Preliminary results**

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A global version of a widely used cloud-resolving model, the System for Atmospheric Modeling (SAM), has recently been developed. The time and cost of development have been minimized by preserving most features and numerics of the SAM's existing anelastic non-hydrostatic dynamical core while generalizing it from Cartesian to latitude-longitude grid. The model uses a single-moment bulk microphysics, comprehensive radiation transfer module, the Simplified Land Model (SLM) with 16 IGBP land types, single layer of vegetation, multilayered interactive soil, and a block representation of topography in height coordinates. The preliminary results of global cloud-resolving simulations for the DYAMOND project with 4, 8.5, and 17 km will be presented. The results of several standard dry-dynamical core tests will be also shown.

**Afternoon session: Topic I / 55**

## **Vertical flux of horizontal momentum: a good use of resolution**

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We study a two-year global nonhydrostatic atmosphere simulation on a 7km mesh (G5NR from NASA's GEOS-5 model) to elucidate the upscale energy flux due to convective momentum transport ( $u'w'$  and  $v'w'$ ) by explicit air motions in the mesoscale (7-444 km) scale range. A global climatology indicates that the resolved mesoscale motions overall act as positive viscosity (damping the shear kinetic energy SKE) on average. However, the variance is spiky, and cases of positive SKE tendency are also seen. We drill down into full-resolution data for selected situations to expose the nature of the calculation and the phenomena involved. Cyclones in shear are especially prodigious in producing convection-momentum interactions, of both signs, through preferential sampling of non-average low-level momentum.

**Afternoon session: Topic I / 279**

## **The added value of hecto and kilo meter scales for the representation of clouds and precipitation**

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In this talk we summarize our experiences in the German national project, high-definition clouds and precipitation for climate prediction, focusing on the added value of high resolution. Simulations using ICON over different domains are presented, the maritime continent and East-Asia, Germany, the Tropical Atlantic, and the North Atlantic, using models with grid spacings ranging from 155 m to 2.5 km and are contrasted with results from climate and NWP models running grid spacings ranging from 10 km to 100 km. The result show that, consistent with a great body of previous work, the ability to resolve precipitating system increases their representation and statistics in manifold ways, but that most of the gains are realized already at grid spacings of 2.5 km. Few qualitative changes are evident as the resolution is reduced finer to to the hectometer scale. Clouds on the other hand are more sensitive to the grid spacing across this range of scales. Many of their features change qualitatively and become more realistic as the resolution approaches hectometer scales; but even at a resolution of 155 m, deficiencies remain. The implications are that advances in computing may greatly advance our ability to represent precipitation in the climate system, as well as the circulation systems underpinning different cloud regimes, making their parameterization more straightforward.

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## Conference Closing