Understanding
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Abstract book
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Exploiting additional observables in the development of an advanced categorization scheme for detecting autoconversion from ground based observations

Autoconversion describes the mass transfer rate from cloud droplets to embryonic drizzle particles. This process plays a key role in the atmospheric water cycle and for the short and long wave cloud radiative forcing in our climate system. Several parameterizations for autoconversion have been proposed for numerical models of varying scales. However, verification of the proposed schemes and their details (e.g., what is the typical size range of the embryo drizzle particles) remains not well understood, primarily due to the fact that it cannot be identified with any direct observations. The use of ground-based remote sensors provides information on the vertical structure of clouds. However, the early detection of drizzle in clouds remains challenging for commonly used target classification schemes (e.g., Cloudnet). Here, we focus on a novel, more advanced approach based on higher Doppler spectra moments (as opposed to the "standard" moments reflectivity, mean Doppler velocity and Doppler spectrum width) obtained from the MIRA cloud radar at JOYCE (Jülich Observatory for Cloud Evolution) and from the synergy of a variety of instruments present. One of these higher moments is the skewness of the radar Doppler spectrum. Normally, cloud droplets without any significant fall velocity but under the influence of turbulence will lead to a Gaussian Doppler spectrum (i.e. skewness is zero), whereas the onset of drizzle will lead to a deviation from the ideal Gaussian form (i.e. positive skewness at first). This basic idea is exploited to develop new criteria to detect drizzle onset within clouds. The criteria is based on the statistical distributions of unambiguously determined drizzling and non-drizzling clouds. A statistical probability for belonging to the non-drizzling, respectively the drizzling population is calculated based on the moments of the Doppler spectrum. In order to minimize instrument and skewness estimator noise, a prefiltering skewness mask is applied first, which selects adjacent radar pixels with positive skewness values. The new method has been tested on individual cases at JOYCE and has shown to identify potential areas of drizzle formation within the cloud. The criteria is also being applied to a longer dataset of liquid warm clouds to statistically evaluate the performance compared to previous drizzle detection criteria, in view of possible operational applications. We project, that our new method can provide new observational constraints for autoconversion parametrizations in numerical models. Additional sensitivity studies on IQ raw cloud radar data have also been performed to evaluate the accuracy of higher moments estimates and their sensitivity to basic radar parameters, like the number of FFT points in the radar Doppler spectrum and number of spectral averages. By this, the optimum radar settings are identified for highest sensitivity in the specific context of applications concerning drizzle detection in warm clouds.
Nowadays, climate simulations are of high societal relevance. In order to reduce significantly the uncertainty of climate change projections, it is crucial to understand cloud and precipitation processes. Within the HD(CP)2 project an LES model based on ICON (ICOshedral Non hydrostatic GCM) is being developed. The ICON-LES model aims at resolving cloud and precipitation processes using grids with a resolution of 10000x10000x400 grid elements and a grid spacing of 100m. Such simulations are computationally very intensive and can be done only on massively parallel computing platforms consisting of hundreds of thousands of cores with distributed memory. Consequently, the memory scalability of the code is vital for being able to fully exploit such HPC platforms. In ICON several global data fields prohibited the execution of experiments with a resolution in the range of O(100m). For solving this problem a major refactoring of the code has been undertaken. Thereby, all the global fields were substituted with distributed data structures and the corresponding algorithms were parallelized. High scaling tests on JUQUEEN in FZJ show that the refactored HD(CP)2 model can now run experiments with a grid resolution of 120m on up to 458752 cores, which are all that are available on JUQUEEN, and which far exceeds our target of 100K cores we set at the beginning of the project. For its excellent scaling behaviour our model has been elected to the High-Q club, which consists of a limited number of codes that can efficiently utilize the entire JUQUEEN machine.
Adler, Bianca

Karlsruhe Institute of Technology

bianca.adler@kit.edu

Low-level cloud formation in southern West Africa during the monsoon period

During the monsoon season, southern West Africa is frequently affected by an extensive low-level stratiform cloud cover only few hundred meters above the ground, which forms during the night. These clouds are likely associated with a nocturnal low-level jet, which blows from the south-west during the monsoon season. Ground- and space-based observations reveal that the stratiform clouds often persists into the day, followed by a transition to convective clouds around midday. Within the framework of the Dynamics-aerosol-chemistry-cloud interactions in West Africa (DACCIWA) project, a field campaign will take place in southern West Africa in summer 2016 aiming – amongst others – to investigate the formation and dissolution of the low-level stratiform clouds. In preparation of this field campaign, we performed numerical simulations with the Consortium for small-scale modelling (COSMO) with a horizontal grid spacing of 500 m and 80 vertical levels. The model is able to reproduce the diurnal cycle of clouds from the formation of stratiform clouds to the transition of convective clouds. We investigated the processes relevant for the cloud evolution and distribution and performed sensitivity tests. The cloud characteristics (layer depth, horizontal extent, diurnal cycle) were insensitive to changes in the model domain and in the turbulence parametrization.
Ament, Felix

Max Planck Institute for Meteorology

felix.ament@uni-hamburg.de

Observing precipitation structures at the 100m scale

Co-authors: Patrick Hartung, Marco Clemens, Verena Grützun, Katharina Lengfeld, Andrea Lammert

Convective motion and evolution of clouds and precipitation becomes apparent not before very small scales of minutes in time and 100 m in space are considered. Accordingly just simulations by eddy-resolving numerical models feature detailed complex evolutions of cloud life cycles and corresponding precipitation patterns. But are these structures realistic? Novel observational techniques at the relevant scales and appropriate evolution techniques are needed to answer this question. Local area precipitation radar at x-band frequency can observe precipitation at LES scales. We will present a multi-year deployment of five radars to observe precipitation with 100-250 m resolution at 30 s intervals. In particular, we will focus on the algorithms to derive precipitation products and on a scheme to correct for attenuation effects by using additional coarse scale C-band radar information. Due to the chaotic nature of convective we needed evaluation methods comparing the behavior of convective motion rather than verifying a grid point wise match. In the second part of the presentation will discuss such a methodology: By using a simple tracking scheme, it is possible to distinguish between advective changes in the precipitation field and changes due to the evolution of precipitation cells itself. We diagnose the ratio of both change rates independently in observations and simulations. This information can be used to assess the realism of model simulations.
Baars, Holger

TROPOS

baars@tropos.de

A new methodology to estimate vertical profiles of CCN and INP number concentrations from polarization aerosol lidar measurements

We investigate the potential of polarization lidar to provide vertical profiles of aerosol parameters from which cloud condensation nucleus (CCN) number concentration and ice nucleating particle (INP) number concentration can be estimated. We show that height profiles of number concentrations of aerosol particles with radius greater than 50 nm (APC50, reservoir of favorable CCN) and with radius greater than 250 nm (APC250, reservoir of favorable INP), as well as profiles of the aerosol particle surface area concentration (ASC, a relevant quantity in INP parameterization) can be retrieved from the lidar derived aerosol optical properties with relative uncertainties of a factor of 2-3 (APC50), and 20-30% (APC250, ASC). Our investigation of the relationship between the aerosol particle extinction coefficient (AEC, measurable with lidar) and APC50, APC250, and ASC is based on multiyear Aerosol Robotic Network (AERONET) photometer observations of the spectral aerosol optical thickness (AOT) together with the column-integrated particle size distribution. We derive APC50-to-AEC, APC250-to-AEC, and ASC50-to-AEC conversion ratios for the common laser wavelengths of 355, 532, and 1064 nm, and this for the basic aerosol types (mineral dust, maritime aerosol, continental pollution). Measurements from Leipzig, Germany and the new HD(CP)2 model domain locations of Cape Verde and Barbados have been investigated which cover most realistic aerosol mixtures. By means of published INP parameterization schemes we compute INP number concentration profiles from APC250 and ASC profiles, and apply these parameterizations to lidar measurements of a heavy dust outbreak at Barbados, a dust-smoke plume at Cape Verde, and a strong anthropogenic pollution event over Leipzig, with aerosol layers up to 5 km height.
Ban, Nikolina

ETH Zurich

nikolina.ban@env.ethz.ch

**Convection-Resolving Climate Change Simulations: Short-term precipitation extremes in a changing climate**

Climate change projections of precipitation are of great interest due to potentially important hydrological impacts such as droughts, floods, erosion, landslides and debris flows. For the southern part of the European continent, climate models consistently project substantial decreases in mean summer precipitation in response to greenhouse gas forcing. Despite this trend towards dryer conditions, many models also project increases of heavy precipitation events, and some observational studies have raised the possibility of dramatic increases in hourly events (by up to 14% per degree warming). However, conventional climate models are not suited to assess short-term heavy events due to the limited spatial resolution and the associated need to parameterize convective precipitation (i.e. thunderstorms and rain showers). Here we employ a convection-resolving model with explicit (rather than parameterized) convection using a horizontal grid spacing of 2.2 km across an extended region covering the Alps and its larger-scale surrounding from northern Italy to northern Germany. Validation of the convection-resolving model reveals major improvements relative to parameterized convection (12 km grid spacing), in particular regarding the representation of short-term precipitation extremes. Climate-change projections are conducted for an RCP8.5 greenhouse gas scenario for the end of the current century. Comparison of explicit versus parameterized convection reveals close agreement regarding a significant decrease of mean summer precipitation, which is consistent with previous studies. However, unlike previous studies, we find that both extreme daily and hourly precipitation events asymptotically intensify with the Clausius-Clapeyron relation (i.e. 6-7%/K) and not with the super-adiabatic scaling rate (≈14%/K).
Bao, Jian-Wen

NOAA/OAR/ESRL

Jian-Wen.Bao@noaa.gov

Which Cloud-Microphysical Processes Contribute to the Difference in the Simulated Development of an Idealized 2-D Squall Line?

In this study, numerical model simulations of an idealized 2-D squall line are investigated using microphysics budget analysis. Four commonly-used microphysics schemes ranging from the one-moment bulk to the two-moment bulk and to the spectral bin schemes are used in the simulations with two different horizontal grid spacings: \( \Delta x = 1 \) and 0.25 km (with identical vertical grids). Diagnoses of the source and sink terms of the hydrometeor budget equations reveal that the differences related to the assumptions of hydrometeor size-distributions between the schemes lead to the differences in the simulations due to the net effect of various microphysical processes on the interaction between latent heating/evaporative cooling and flow dynamics as the squall line develops. Results from this study also highlight the possibility that the advantage of double-moment formulations can be overshadowed by the uncertainties in the spectral definition of individual hydrometeor categories and spectrum-dependent microphysical processes.
Barthlott, Christian

*Karlsruhe Institute of Technology*

christian.barthlott@kit.edu

**Impact of model domain, grid spacing, and microphysics scheme on the simulation of deep convection over Germany during Pentecost 2014**

During Pentecost 2014, central Europe was affected by an unusually high number of convective systems leading to severe damages due to strong winds, heavy precipitation, hail, and lightning. In Germany, wind gusts of 144 km/h were observed at Duesseldorf airport and maximum temperatures reached nearly 38 degrees C in southwestern Germany. An almost stationary low pressure system over the northern Atlantic and a ridge stretching from Africa to northern Europe led to very high low-level temperatures due to advection of warm air in combination with solar insolation. We present convection-permitting numerical simulations for two days of this event (8 and 9 June 2014) using the COsortium for Small-scale MOdeling (COSMO) model. Whereas a reference run with more or less operational settings was successful in reproducing the convective events of the first day, it failed to adequately reproduce the events of the second day. Several sensitivity studies with an enlarged model domain, increased horizontal and vertical grid spacing, different model initialization times, and using a more sophisticated 2-moment microphysics scheme are conducted to investigate the reasons for model deficiencies and convection initiation in general.
Baumgartner, Manuel

*Johannes Gutenberg University Mainz*

manuel.baumgartner@uni-mainz.de

**Diffusion processes in mixed-phase clouds involving direct particle interactions**

Clouds containing ice particles are important for the Earth-Atmosphere system. They modulate the radiation budget by a combination of albedo effect and greenhouse effect. In contrast to liquid water clouds, the radiative impact of clouds containing ice particles is still uncertain. Scattering and absorption highly depends on microphysical properties of ice crystals, e.g. size and shape. In addition, most precipitation forms via the ice phase. Thus, better understanding of ice processes is required. A key process for determining shape and size of ice crystals is diffusional growth of ice particles and water droplets, especially inside mixed-phase clouds. Diffusion processes in mixed-phase clouds are highly uncertain; in addition they are usually highly simplified in cloud models, especially in bulk physics parameterisations. Generally, the direct interaction between cloud droplets and ice crystals is ignored; particles can only interact via their environmental conditions. Local effects as supply of supersaturation due to clusters of droplets around ice particles are usually not represented. We present an approach to parameterize the direct interaction by diffusion of cloud particles (liquid and solid). This parameterization includes the local competition of ice particles and droplets for the water vapour, leading to the Wegener-Bergeron-Findeisen process. We consider the local steady-state solutions of the diffusion equation for water vapour for an ice particle as well as a droplet. These solutions are coupled together to obtain the desired interaction. We present the derivation of this bulk microphysics scheme and show some results of the scheme as implemented in a parcel model. (together with Peter Spichtinger)
Becker, Tobias

Max Planck Institute for Meteorology
tobias.becker@mpimet.mpg.de

The structure of large-scale convective circulations comparing GCM and LES simulations

Convective circulations can organize in various ways and over multiple scales. In this study, the general circulation model ECHAM6 directs attention to the large-scale organization of convection, which will be compared in a second step to convective organization in a deep convection resolving version of ICON. The radiative-convective equilibrium setup provides a good comparability of GCM and LES experiments and ensures a focus on the basic drivers of convection – radiation, tropospheric humidity and surface fluxes. In ECHAM6, the interaction of precipitating convection with the large-scale environment is investigated by altering the convection scheme and the surface temperature. The degree of convective aggregation strongly depends on the entrainment rate. If no environmental air is mixed into the convective updraft, convection is rather disaggregated, while it is extremely aggregated if the parameterization of subgrid-scale convection is switched off, which is analogue to an infinite entrainment rate. If the entrainment rate is in a certain range, the degree of convective aggregation depends on surface temperature. Subsidence fraction, a large-scale property that is important for radiative transfer, increases both at very high and low surface temperatures, indicating an increase of convective aggregation. Convective organization increases at high temperatures on the one hand because entrainment decreases the updraft buoyancy more efficiently, and on the other hand because a shallow overturning circulation induces an upgradient moist static energy transport. At low temperatures, convective organization increases because the longwave cooling in subsidence areas induces a strong overturning circulation with strong surface winds at its edges, and because convection is more closely coupled to the surface fluxes. The aim of the further analysis is to enhance understanding of cloud-radiation and moisture-convection feedbacks and to derive effective coupling parameters and relate those to assumptions used in the parameterization of convection.
Beekmans, Christoph

Institute for Meteorology Bonn
cbeekmans@uni-bonn.de

3D Cloud Morphology and Motion from a Network of Sky Imagers

Christoph Beekmans, Clemens Simmer

Sky imagers provide a full hemispheric view of the visible sky with high temporal and spatial resolution due to their mounted ultra-wide angle fisheye lens. In combination with modern computer vision and photogrammetric techniques they offer valuable information about convective cloud development, such as cloud geometry, convective updrafts, cloud motion, size, type and cloud population in general. Cloud morphology is derived based on observations made by a network of six sky imagers during the HOPE campaign in 2013, and four imagers in follow-up campaigns near the Jülich Observatory for Cloud Evolution (JOYCE), Germany. By focussing on cloud stereo photogrammetry, we are able to reconstruct the complex shapes of single convective clouds with high geometric integrity and over a large field of view. In contrast to existing approaches, we use a global and dense stereo technique that is able to consistently reconstruct whole surface sections of clouds directly, instead of a sparse 3D point set from classical feature-based approaches. The resulting cloud geometries are compared with the cloud base height data from a lidar-ceilometer, and the cross-section scans from the cloud radar, which are both located at the JOYCE supersite. The application of optical flow algorithms on time series of sky images, yields a spatially dense motion vector field with respect to the 3D cloud surface. Cloud motion speed is validated by the local wind-lidar for a cloud layer. Our results show that dense photogrammetric stereo in combination with the large field of view offered by sky imagers is able to produce very high detail cloud geometries that are consistent in time, and capture the complex shapes often encountered during cloudy conditions. A further spatial coverage of the sky imagers would offer an important data source for radiation closure studies and small-scale model validation.
Behrendt, Andreas

University of Hohenheim

andreas.behrendt@uni-hohenheim.de

Atmospheric Boundary Layer Studies with combined Temperature Rotational Raman Lidar, Water Vapor Dial, and Doppler Lidar

Andreas Behrendt1, Volker Wulfmeyer1, Eva Hammann1, Shravan Kumar Muppa1, Florian Späth1, Simon Metzendorf1, Andrea Riede1, Norbert Kalthoff2, Vera Maurer2, Andreas Wieser2 1: University of Hohenheim, Institute of Physics and Meteorology, Stuttgart, Germany 2: Karlsruhe Institute of Technology, Institute for Meteorology and Climate Research, Karlsruhe, Germany.

Thermodynamic fields of temperature and moisture including their turbulent fluctuations have been observed with the two scanning lidar systems of University of Hohenheim in three recent field campaigns, including the HOPE campaign in 2013. In this contribution, we will introduce these two self-developed instruments and illustrate their performance with measurement examples. The combination of these water vapor and temperature lidar instruments with Doppler lidar allows for deriving co-variances such as latent and sensible heat fluxes. First sensible heat flux profiles measured with lidar will be presented. Finally, an outlook to envisioned future research activities with the new data sets provided by these instruments is given.
Bennartz, Ralf

University of Wisconsin / Vanderbilt Univ.

ralf.bennartz@vanderbilt.edu

**Integral constraints on cloud and precipitation processes**

Constraining and quantifying the role of ice- and mixed-phase microphysical processes remains a challenge both in terms of process understanding and model parameterizations. My hypothesis is that the microphysical variability we are seeing is described largely 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 used to validate and narrow down uncertainties in cloud microphysical parameterizations. The work presented here expands on earlier studies where we have developed a similar process understanding for warm rain processes. Here, I will address the relative importance of riming, aggregation, and ice particle diffusional growth in high-latitude precipitation generation. Various long-term ground-based in-situ and remote sensing datasets are used to describe precipitation intensity and type and its relation to the state of the atmosphere. The relative importance of these processes appears to vary strongly between different precipitation events. This study draws heavily on datasets obtained by our NSF-funded Integrated Characterization of Energy, Clouds, Atmospheric state, and Precipitation at Summit, Greenland (ICECAPS) experiment, which, because of its high and cold location, provides a unique opportunities to study ice microphysical processes.
Bley, Sebastian

TROPOS

bley@tropos.de

Comparison of the spatio-temporal scales of modeled ICON-LES and observed convective cloud fields

Small-scale convective clouds are highly variable in space and time and cover large areas of the globe. They couple the boundary layer and the free troposphere through the transport of energy and moisture. Their variability complicates a realistic representation in numerical models, but also introduces significant uncertainties in satellite retrievals. Thus intercomparisons between observations and high resolution models are essential in order to better understand observational and model uncertainties. Our main focus is on the identification of characteristic temporal scales of convective cloud fields. For this purpose, we use observations from METEOSAT SEVIRI from the Rapid Scan Service with a 5 minute temporal resolution. The high resolution visible (HRV) channel with a spatial resolution of 1x2km$^2$ is of particular value for our study as it allows tracking of small-scale convective cloud structures. We determine the time-lagged auto-correlation function for 48x48 HRV-pixel boxes and calculate the decorrelation times for different cases, adopting both an Eulerian and a Lagrangian perspective. Decorrelation lengths are also estimated through a displacement of the box. When adopting the Lagrangian perspective, nearly all cases show constant decorrelation times of around 30 minutes. In contrast, a strong dependency of the Eulerian decorrelation times on the horizontal velocity of the cloud fields is found. This behavior corresponds to that expected for stationary ground-based measurements. To evaluate the ICON-LES which was developed within HD(CP)2 we apply the spatio-temporal analysis that is already performed with observations to the model output. The modeled convective cloud fields are used to study the resolution dependency of our observational analysis. Finally, implications of the deviations between observations and models for the representation of convective clouds are discussed.
Blyth, Alan

National Centre for Atmospheric Science

Alan.Blyth@ncas.ac.uk

Heavy precipitation in SW England: the importance of dynamics and microphysics interactions

Measurements made during the Convective Precipitation Experiment are used in conjunction with a high spatial and temporal resolution model to determine the interactions between the dynamics and microphysics that are so important for the development of heavy precipitation leading to flash flooding. The measurements were made with two aircraft, a mobile radar, and a network of permanent radars. The research aircraft were the University of Wyoming King Air uniquely with the cloud radar and lidar, the UK BAe146 aircraft with microphysics and aerosol instruments. The mobile radar is a dual-polarisation Doppler X-band radar that made PPIs with a volume return time of just under 5 minutes. 1-min output of 400-m resolution WRF runs and a detailed microphysics model were used to help interpret the observations. A physical description will be presented of cases on 2 and 3 August, 2013. Convection formed along convergence lines likely generated by colliding sea-breeze fronts. Heavy precipitation was produced similar to, but weaker than the Boscastle flash flood. Aerosols (measured below cloud base with the BAe146) played an important role. However, the dynamics were key to the behaviour of the individual clouds and the development of the precipitation particles. Whether or not supercooled raindrops were important in the production of ice; the presence or otherwise of multiple thermals with high liquid water content cores, so essential for the growth of embryos and the production of secondary ice particles; the transfer of particles (seeding) between thermals; and the persistence of heavy precipitation in one location, were all dependent on the dynamics. The information gathered, although immense, is perhaps not as disparate as the session seeks. However, nearly 35 years after the much larger Cooperative Convective Precipitation Experiment, we must ask what progress is being made, what questions remain challenging and what new measurement strategies are needed.
Bomidi, Lakshmi Madhavan

TROPOS

madhavan.bomidi@tropos.de

On the scale dependence of cloud induced radiation fields at the surface for closure studies

Clouds modulate significantly the Earth’s radiation budget through their interaction with solar and terrestrial radiation. Due to their complex shape, morphology and degree of inhomogeneity, they are considered as the most complex objects in both spatial and temporal scales of Earth’s atmosphere with contribution to uncertainty in climate and weather predictions. Within the frame work of High Definition Clouds and Precipitation for advancing Climate Prediction (HD(CP)²) Observational Prototype Experiment (HOPE), a high density network of 99 pyranometer stations was set up around Juelich, Germany (~ 10 × 12 km² area) during April to July 2013 to capture the small-scale variability in cloud induced radiation fields at the surface. In this study, we perform multi-resolution analysis with wavelets on the observed variability of global flux transmittance fields at the surface from the pyranometer network. We investigate (i) the effect of temporal averaging on the variance, (ii) scale dependence of spatial correlation lengths, and (iii) the degree of representativeness of point measurements with area averaged values for different days with variable sky conditions (clear, cirrus, overcast and broken clouds). It was observed that the time series of transmittance fields on broken cloudy days exhibited significantly higher and distinct variability at all averaging frequencies. In general, the variability in transmittance increased with decreasing frequency and vice versa, irrespective of the prevailing cloud cover. Further, the spatial correlation is strongly scale-dependent while the variance is dependent on the length of averaging period. In addition, the variance in the area averaged values decreased with increasing area of averaging and increased with decreasing frequency of power spectrum. The details of our findings will be presented along with their implications on the closure studies involving small scale variability of cloud inhomogeneity fields.
Brient, Florent

ETH Zurich

florent.brient@erdw.ethz.ch

**Constraints on climate projections from temporal variations of tropical low clouds**

The dominant source of uncertainties in climate change projections is how clouds feed back onto surface warming. Current models project Earth to warm by between 2.6 and 4.5°C by the end of the 21st century under a scenario of relatively high carbon dioxide emissions (RCP8.5); 70% of the spread among models is attributable to differences of how their tropical low clouds respond to warming. We use 15 years of space-based measurements of radiative properties of tropical low clouds to evaluate the fidelity of different climate models. We decompose the temporal variability into four frequency bands, which allows us to discriminate cloud responses to natural variability on different timescales. We show that the shortwave reflectivity of tropical low clouds decreases as temperatures increase, providing a positive feedback on warming. Only climate models with a strong positive cloud feedback are consistent with observations, suggesting that the warming to be expected over this century will likely fall into the upper half of the range currently projected by climate models.
Shallow Cumulus response to surface flux perturbations in large-eddy simulations

Florent Brient, Tapio Schneider, Zhihong Tan, Kyle Pressel

High-resolution large-eddy simulations (LES) can successfully reproduce marine low-clouds as observed in field studies (e.g. BOMEX, RICO, DYCOMS). Recently, continuous space-based observations of clouds have become available, and allow test of LES in a wider range of circumstances, including the seasonal cycle. Here we use a recently developed LES code called PyCLES, which uses specific entropy and total water specific humidity as prognostic variables and discretizes the equations of motion with high-order weighted essentially non-oscillatory (WENO) numerical schemes. Using PyCLES, we simulate the seasonal cycle of tropical marine boundary layer clouds in selected locations. We investigate the similarity, or lack thereof, of the response of low clouds to seasonal variations and global warming, with the goal of identifying the mechanisms responsible for this low-cloud response.
Brueck, Matthias

University of Leipzig

matthias.brueck@uni-leipzig.de

Water vapor and cloud condensate variability simulated by statistical cloud parametrizations in the global ICON model

Parameterizations of cloud processes are generally unresolved by the numerical resolution of present day and future general circulation models used for climate prediction. A promising approach is to base cloud parameterizations on assumed subgrid-scale variability of total (cloud condensate and water vapor) water, expressed by a subgrid-scale probability density function (PDF). Traditional cloud parameterizations diagnose cloud fraction from grid-box mean quantities (e.g. RH), while new schemes implicitly try to capture the underlying cloud processes. Following the latter approach clouds can respond to a warming climate in a physically consistent manner. Additionally the total water PDF can be shared by other cloud related parameterizations which increases model consistency. Well established and recently developed cloud parameterizations (e.g. EDMF-DualM, CLUBB) are reviewed and their skill to simulate variance and skewness of the total water PDF is analyzed. Being a subproject of the HD(CP)2-initiative we use the icosahedral general circulation model (ICON) with 50 to 100 km horizontal resolution, satellite observations and large eddy simulation to exploit and evaluate the behavior of cloud parameterizations under different dynamical regimes.
Bühl, Johannes

*TROPOS*

johannes.buehl@tropos.de

**Observing the balance between ice nuclei and ice particles in mixed-phase clouds**

The process of ice nucleation plays a crucial role for the hydrological cycle on Earth. It influences the lifetime of clouds and can be a key element in the early stages of rain initiation. Therefore, direct observations of ice nucleation events in the atmosphere are crucial for quantitative insight into this complex process. Recently, DeMott (2010) provided a general description of the ice nucleating ability of aerosol particles, thus the estimation of available ice nuclei, e.g., from lidar measurements becomes possible for the first time. On the other hand, sophisticated combined remote sensing methods like Cloudnet allow detailed insight into the properties of ice crystals originating from cloud layers. In this context, combined observations with Raman/Depolarization lidar and radar show show a high synergistic potential because of they sense the properties of both aerosol particles and ice crystals at the same time. In this work, results of a measurement campaign at the Meteorological Observatory Lindenberg, Germany are presented. For the time period of four month a PollyXT Raman/Depolarization lidar, Doppler lidar, cloud radar and wind profiler were operated together to capture the full picture of aerosol properties, vertical motions, ice and liquid water properties in and around layered clouds. The number of ice nuclei in an aerosol layer surrounding a cloud is estimated via the parameterization of DeMott (2010). The number of ice nuclei falling from an ice cloud is estimated at the same time via radar measurements. It is shown that both quantities can be used to gain detailed, quantitative knowledge about the process of ice nucleation in layered clouds.
Bui, Hien

*University Sinica Taiwan*

bxhien@gate.sinica.edu.tw

**The Role of Shallow Convection in Tropical Climate: Moist Static Energy Framework**

Interactions between cumulus convection and its environment are hardly measured by conventional framework and difficult to represent in the climate models. In this study, we employed the moist static energy (MSE) budget to investigate the potential impact of shallow convection from both reanalysis data and model simulation. A case study is applied over western and eastern Pacific dominated by deep and shallow convection, respectively. The column-integrated MSE vertical advection (iMSEa) of deep convection is positive, while that of shallow convection is negative. This implies deep convection exports MSE to stabilize the atmosphere, but shallow convection imports MSE to destabilize the atmosphere favorable to development of deep convection. Controlling factors of iMSEa for the processes related to deep and shallow convection are discussed. Increasing moisture tends to reduce iMSEa, while a change in dry static energy has little impact. Deeper deep convection tends to have greater iMSEa. For shallow convection, both moister low-level and drier mid-level moisture reduce the vertical MSE advection.
Burdanowitz, Jörg

Max Planck Institute for Meteorology

joerg.burdanowitz@mpimet.mpg.de

Error estimation of HOAPS satellite precipitation estimates using OceanRAIN in-situ ship data

Limited temporal sampling and rather coarse spatial resolution constrain the accuracy of precipitation estimates from passive microwave satellite sensors, such as SSM/I and SSMIS that are used in the Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite data (HOAPS) climatology. Thus, the validation of HOAPS precipitation demands high-quality ground-based precipitation data—a requirement that is very challenging to meet over the global ocean. The Ocean Rainfall And Ice-phase precipitation measurement Network (OceanRAIN) is to date the first systematic ship-board long-term precipitation data collection effort over the global ocean. OceanRAIN samples quantitative precipitation data derived from particle size distributions (PSDs) collected by optical disdrometers that are deployed on research vessels (RV). Valuable meteorological ancillary data serves as input to an automatic algorithm within OceanRAIN to derive the precipitation phase in order to optimally determine the precipitation intensity from PSDs. The used optical disdrometer ODM470 was developed specifically to measure under high wind speed and sea state. The instrument’s suitability for oceanic measurements and the dense data sampling in all climatic ocean regions qualify OceanRAIN for validating and error-characterizing the HOAPS precipitation satellite climatology. The collocation of observations from OceanRAIN and HOAPS raises one of the major challenges in geosciences—the point-to-area issue. While OceanRAIN samples along-track point measurements at 1-minute resolution, HOAPS estimates instantaneous areal precipitation rates in pixels of about 50 kilometers in diameter with few satellite overpasses per day. A collocation matches all OceanRAIN measurements within a HOAPS pixel that are averaged thereafter. A direct OceanRAIN–HOAPS comparison assumes that OceanRAIN measurements well represent areal precipitation within a HOAPS pixel. First results indicate that HOAPS underestimates the occurrence of precipitation and slightly underestimates the precipitation intensity. This presentation will investigate the reasons for these differences and provide insight into the HOAPS precipitation error characterization.
Non-equilibrium ice cloud macrophysics in a large scale model

Observational data show large frequencies of supersaturation relative to ice in the upper troposphere, with ice clouds forming only at large ice supersaturations and persisting at ice saturation. This contrasts cloud parameterizations that infer ice cloud cover from relative humidity or water fluctuations in the same way as for warm clouds or simply shift ice cloud formation and dissipation to the same critical mixing ratio at fixed ice supersaturation. We implement in the ICON-GCM a non-equilibrium ice cloud cover based on a relative humidity scheme by leaving the purely diagnostic framework and introducing a prognostic ice cloud cover variable. Tendencies of the prognostic ice cloud cover are inferred from the PDF underlying the cloud scheme. We analyze the impact of this hysteresis behavior on the ice cloud properties and the upper tropospheric water budget.
Carbajal Henken, Cintia

*Free University Berlin*

cintia.carbajal@wew.fu-berlin.de

**MERIS full-resolution total column water vapor: observing horizontal convective rolls**

The study presents the first analysis of small-scale convective structures observed in a total column water vapor (TCWV) field obtained from full-resolution Medium Resolution Imaging Spectrometer (MERIS) near-infrared measurements. The high-resolution MERIS TCWV field for a high-pressure event occurring in May over central-Europe allows the detailed detection of horizontal convective rolls, due to the observation of parallel bands of alternating low and high TCWV values. The bands are aligned parallel to the boundary layer winds obtained from a numerical weather prediction model and radiosonde data. Closer examination further reveals that cloud streets observed in the east extend along bands of maximum TCWV. From a quantitative analysis of the TCWV data, combined with auxiliary data, it is shown that the roll wavelength and aspect ratio can be determined, which are found to be 6.5 km and 5, respectively, for this case study.
Chaboureau, Jean-Pierre

University of Toulouse & CNRS
jean-pierre.chaboureau@aero.obs-mip.fr

Effect of Turbulence Parameterization on Assessment of Cloud Organization

This study evaluates the cloud and rain cell organization in space and time as forecasted by a cloud-resolving model. The forecast fields, mainly describing mesoscale convective complexes and cold fronts, were utilized to generate synthetic satellite and radar images for comparison with Meteosat Second Generation and S-band radar observations. The comparison was made using a tracking technique that computed the size and lifetime of cloud and rain distributions and provided histograms of radiative quantities and cloud-top height. The tracking technique was innovatively applied to test the sensitivity of forecasts to the turbulence parameterization. The simulations with 1D turbulence produced too many small cloud systems and rain cells with a shorter lifetime than observed. The 3D turbulence simulations yielded size and lifetime distributions more consistent with the observations. As shown for a case study, 3D turbulence yielded longer mixing length, larger entrainment, and stronger turbulence kinetic energy inside clouds than 1D turbulence. The simulation with 3D turbulence had the best scores in high clouds. These features suggest that 1D turbulence did not produce enough entrainment, allowing the formation of more small cloud and rain cells than observed. Further tests were performed on the sensitivity to the mixing length with 3D turbulence. Cloud organization was very sensitive to in-cloud mixing length and the use of a very small value increased the number of small cells, much more than the simulations with 1D turbulence. With a larger in-cloud mixing length, the total number of cells, mainly the small ones, was strongly reduced.
Chechin, Dmitry

*Obukhov Institute of Atmospheric Physics RAS (Moscow)*

dechchin@ifaran.ru

**Convective boundary layer development during cold-air outbreaks in the Arctic: entrainment, clouds and low-level jets**

Idealized simulations of the convective boundary layer development during cold-air outbreaks in the Arctic are carried out by a 3D non-hydrostatic atmospheric model using horizontal grid spacing ranging from 500 m to 5 km. A good agreement with aircraft observations in the Fram Strait is demonstrated with respect to temperature, specific humidity and height of the atmospheric boundary layer (ABL). To a large extent, this is due to using a nonlocal turbulence closure. The latter is modified to take into account entrainment at the top of the atmospheric boundary layer (ABL) and also the presence of clouds in the ABL. Sensitivity of the ABL parameters to the entrainment strength and latent heat release in clouds is quantified. It is shown that a better agreement with observations is obtained by taking these processes into account. However, both entrainment and latent heat release play a secondary role in the ABL modification compared to heating by sensible heat flux from the surface. Low-level jets (LLJs) are another simulated feature of cold-air outbreaks. They occur in the ABL due to baroclinicity associated with the ABL heating. LLJs have a strong impact on surface fluxes of heat and momentum. It is shown that strength and occurrence of LLJs is influenced both by the large-scale characteristics of the marginal sea ice zone and also by the meso-scale variability of the sea ice concentration field. It is shown that the strength of the simulated LLJs is very sensitive to the model resolution.
Chen, Ying-Wen

Japan Agency for Marine-Earth Sciences

yingwen@jamstec.go.jp

High Cloud Responses to Global Warming Simulated by Two Different Cloud Microphysics Schemes Implemented in the Nonhydrostatic Icosahedral Atmospheric Model (NICAM)

This study examines cloud responses to global warming using a global nonhydrostatic model with two different cloud microphysics schemes. The cloud microphysics schemes tested here are the single- and double-moment schemes with six water categories, which are referred to NSW6 and NDW6, respectively. Simulations of one year for NSW6 and one boreal summer for NDW6 are performed using the nonhydrostatic icosahedral atmospheric model (NICAM) with a mesh size of approximately 14 km. NSW6 and NDW6 exhibit similar changes in the visible cloud fraction under the global warming condition. Larger longwave (LW) cloud radiative feedbacks are found in NSW6 and NDW6 compared with the results from the Coupled Model Intercomparison Project Phase 3 (CMIP3). These large LW cloud radiative feedbacks are mainly attributed to the change of cirrus clouds, which prevail more in the tropics under global warming conditions. For NDW6, the LW cloud radiative feedbacks by cirrus clouds also extend to mid-latitudes. The changes in cirrus clouds and their effects on LW cloud radiative forcing (LWCRF) are assessed based on changes in the effective radii of ice hydrometeors (Rec) and cloud fraction. We found that an increase in Rec has a non-negligible impact on the LWCRF compared with an increase in cloud fraction.
Chen, Cheng-Ta

National Taiwan Normal University

chen@rain.geos.ntnu.edu.tw

Can High Resolution Climate Models Reproduce Rainfall Extremes Associated with Tropical Cyclones?

Hurricane and Typhoon are the major contributors to the annual damage and economic lost due to natural disaster around the world. How the characteristics of these high-impact weather extremes changes in a warming climate have attracted considerable interests from research community. One key uncertainty regarding to the previous studies is the tropical cyclone intensity and associated extreme rainfall are often underestimated. With high-resolution global climate model reached 20-30 km resolution, we found that these high-resolution models can start to reasonably capture the typical wind-pressure relationship found in the observed tropical cyclone. Nevertheless, the composite of rainfall associated with tropical cyclone in the model are several times higher than the corresponding typhoon rainfall estimate from satellite observation (e.g. TRMM). To explain such discrepancy, the possible underestimate from satellite rainfall retrieval for extremes associated tropical cyclone was supported from surface observation during typhoon landing period. The motivation of study is to work on a more throughout examination of the satellite rainfall estimate with surface observation along all the tropical cyclone tracks. For high temporal and spatial resolution near global rainfall analysis, different satellite observations had been used to retrieve and construct the precipitation distribution from the combination of active and passive sensors. Normally surface rainfall observation was used to calibrate the rainfall retrieval scheme. However, they are typically optimized for all rainfall conditions from light shower to heavy downpour. Such strategy in developing retrieval algorithm might loose the dynamical range of observational signal in the heavy rainfall tail end associated with tropical cyclone. Our study co-located the available satellite and surface rainfall observation along the tropical cyclone best tracks data archive and systematically evaluate the characteristics of satellite rainfall estimate during different stages of tropical cyclone life cycle.
Chen, Baode

Shanghai Typhoon Institute of CMA
baode@mail.typhoon.gov.cn

Dependency of the Cloud Morphology of an Idealized Splitting Superstorm on Microphysical Processes and Subgrid Mixing

We will present a study in which numerical simulations of an idealized splitting superstorm using microphysics parameterization schemes of different complexity and varying subgrid mixing lengths in the 3-D TKE turbulence scheme are compared and evaluated in terms of the storm’s morphology. The numerical simulations are carried out using the Weather Research and Forecasting Model (WRF) at resolutions of 3 km, 1 km and 100 m. It is found in this study that the simulated storm morphology varies as the grid size is reduced. The characteristic morphology of the simulated is sensitive to various cloud microphysics schemes and the subgrid mixing lengths. In particular, for simulations of a particular resolution, the simulated storm tends to lose its symmetry as the subgrid mixing length is decreased. The degree of the symmetry loss depends on the complexity of the cloud microphysics scheme. For a particular cloud microphysics scheme and resolution, there appears to be an optimal specification of the subgrid mixing length.
Chen, Sisi

McGill University

sisichen@mail.mcgill.ca

The Evolution of Droplet Size Distribution in Turbulence Clouds

Turbulence is regarded as an important factor in the process of warm rain formation since it increases the chance of droplet collisions. Previous DNS studies have shown that turbulence significantly enhances the collision kernel. To date there are only a few models concerning about the turbulent enhancement on droplet collisions that includes collision efficiency and few DNS studies have shown results of the evolution of droplet size distribution. In this study, we developed a DNS model that include the process of collisional growth. We examined the growth history of droplets with initial radii between 5-25 microns because droplets of these sizes are critical in forming larger droplets that can initiate effective gravitational collisional growth. In order to give a more accurate representation of the background flow that drove droplet motions, our model resolved the disturbance flow induced by the present of droplets (i.e., the hydrodynamical effect). Finally, the evolution of droplet size distributions (DSDs) is investigated as the droplets grew in time by collision and coalescence. We demonstrated the DSD evolution at different turbulence intensities and compared them with the pure gravitational cases.
Chiu, Christine

*University Reading*

c.j.chiu@reading.ac.uk

**Clouds laid bare – A 3D view from scanning radar, lidar and shortwave radiation observations**

Clouds are complicated 3D objects that evolve fast. Long-term ground-based observations have proved invaluable in understanding cloud processes. However, clouds have been observed from a vertically pointing view in the past; consequently, their evolution and 3D structures must be derived based on certain assumptions, making it difficult to tackle cloud problems in a fully 3D situation. The new scanning capability of cloud radar and lidar provides an exciting opportunity to alleviate these issues and to provide robust 3D cloud observations. This talk introduces a novel retrieval method that provides 3D retrievals of cloud and precipitation with full error statistics. The method exploits not only synergetic measurements, but also an ensemble Kalman Filter approach to incorporate 3D radiative transfer, which remains challenging for other retrieval techniques. We will show examples for a wide spectrum of cloud types ranging from small cumulus to complex mixed-phase clouds. Since these synergetic retrievals are simultaneously constrained by multiple instruments, they access properties inaccessible in the simulator approach and will be invaluable for evaluating high-resolution simulations and for understanding cloud processes throughout their life cycles.
Christensen, Hannah

*University of Oxford*

h.m.christensen@atm.ox.ac.uk

**Constraining Stochastic Parametrisation Schemes using High-Resolution Model Simulations**

Convection is generally acknowledged to be the parametrisation scheme to which weather and climate models are most sensitive, so it is important to accurately represent the uncertainty originating in the parametrisation of convection. One proposed technique uses stochastic parametrisation schemes, which seek to represent the variability in unresolved sub-grid scale processes. Stochastic parametrisations have been used for more than a decade in atmospheric models, and have been shown to improve the spread and mean state for medium- and extended-range forecasts (Buizza et al. 1999; Palmer et al. 2009). Through noise induced drift and noise enhanced variability, stochastic parametrisations are also able to improve the climate of an atmospheric model (Berner et al. 2008; Christensen et al. 2015; Dawson and Palmer 2015). However, many successful stochastic parametrisation schemes have limited physical basis. For example, the European Centre for Medium-Range Weather Forecasts (ECMWF) multiplicative scheme ‘Stochastically Perturbed Parametrisation Tendencies’ (SPPT), while very skilful at representing model uncertainty in weather and climate forecasts, involves several assumptions including imposing spatial and temporal correlations that are not based on observations. We propose the use of high-resolution model simulations to explicitly measure the difference between parametrised and ‘true’ sub-grid tendencies: in this way, we characterise the error in the tendency that stochastic schemes such as SPPT seek to represent. In particular, we use data from the CASCADE project as ‘truth’ and focus on regions of tropical convection in the Indian Ocean and West Pacific. It is hoped these measurements will improve both holistic and process based approaches to stochastic convection parametrisation. Berner, J, et al., 2008. Phil.Trans.R.Soc A, 366, 2559–2577 Buizza, R, et al., 1999. Q.J.R.Meteorol. Soc., 125, 2887–2908. Christensen, HM, et al., 2015. Clim.Dynam., 44(7),2195-2214 Dawson, A and TN Palmer, 2015. Clim.Dynam., 44(7),2177-2193 Palmer, TN, et al., 2009, ECMWF technical memorandum 598.
Cioni, Guido

Max Planck Institute for Meteorology
guido.cioni@mpimet.mpg.de

Impact of soil moisture on convective precipitation

Guido Cioni and Cathy Hohenegger

Soil moisture and convective precipitation are generally thought to be strongly coupled, although limitations in the modeling set-up of past studies due to coarse resolutions, and thus poorly resolved convective processes, have prevented a trustful determination of the strength (and sign) of this coupling. Here the soil moisture-precipitation feedback is investigated by mean of high-resolution simulations where convection is explicitly resolved. Idealized simulations mimicking the diurnal cycle of convection over land starting from different soil moisture condition are performed. To that aim we use the LES version of the ICON model, with a grid spacing of approximately 100 m, coupled to the TERRA-ML soil model. Various atmospheric conditions, like different soundings are exploited in order to span the wide range of possible environmental states as a function of initial soil moisture. The results are compared to earlier studies which have used lower resolution.
Colin, Maxime

University of New South Wales and LMD
m.colin@student.unsw.edu.au

The preferred carriers of convective memory in the tropics

In an attempt to improve both the diurnal cycle of tropical convection and the representation of the spatial organisation of convection in General Circulation Models (GCMs), we investigate what the "convective memory" would mean for a convective parameterization. Convective memory is associated with the persistence of clouds in time. It can arise from large-scale processes as well as many different small-scale processes, but here the focus is only on the smaller-scale sources. Some previous studies have tried to include a simple memory of convection in GCMs, but without any strong foundation. Therefore, this study intends to show numerical evidence to help determine the main carriers of convective memory. We perform a suite of idealised Radiative-Convective Equilibrium (RCE) simulations, with the Weather Research and Forecasting (WRF) model, at Cloud-Resolving resolutions. A range of perturbations is introduced to test how convection responds when the small-scale structures of any given prognostic variables are suddenly removed. It seems that water vapour is the strongest carrier of convective memory, but conversely some other variables may carry a form of anti-memory. Ensembles of experiments are used to obtain more statistically significant results. First sensitivity tests on the microphysics scheme and on the dimensionality are carried out in order to estimate the range of validity of the results.
Craig, George

_Ludwig-Maximilians-University Munich_

gleorge.craig@lmu.de

**Theories for convective organization and parameterization developed using high-resolution numerical simulations**

The development of theory and parameterizations for moist convection is made difficult by two factors: the inability to directly measure dynamically important quantities such as cloud mass flux, and the difficulty of isolating cumulus effects in a continuously changing environment. High-resolution numerical simulations can help with these problems, since they allow the full state of the model atmospheric state to be quantified, and allow the use of idealized experimental configurations where environmental effects are greatly simplified. This presentation will consider radiative-convective equilibrium experiments at horizontal resolutions ranging from 2 km to 125 m, in order to identify intrinsic limits of convective parameterization and develop theoretical models that can be used as the basis for stochastic schemes. The theory of Craig and Cohen (J. Atmos. Sci. 2006) for disorganized convection, that underlies the stochastic parameterization of Plant and Craig (J. Atmos. Sci. 2008), will be revisited and three different mechanisms for interactions between convective clouds will be introduced. Under appropriate conditions, these mechanisms lead to different large-scale atmospheric structures including thermalization (damping of large-scale waves), coarsening (separation into wet and dry regions), and self-organized criticality (power law scaling). Some of these behaviors may be captured by the current generation of convection schemes, while others may require new concepts.
Dal Gesso, Sara

*University of Cologne*

dalgesso@meteo.uni-koeln.de

**Can we use Single-Column Models for climate feedback studies?**

The Single-Column Model (SCM) has proven a useful tool for the development, evaluation and improvement of the representation of boundary-layer clouds in large-scale models. Recently, the parametrization of such clouds have been identified as a major contributor to uncertainty in future climate predictions. However, much remains to be understood about the response processes of the boundary-layer clouds. One then wonders if, and if so how, the SCM can be used to make progress. A first step is to assess how representative long-term SCM simulations on climate timescales are of the model climate of their native General Circulation Model (GCM). To this purpose, 30-year simulations are performed with the SCM version of EC-EARTH GCM, that are forced by high-frequency cfSites output of the CFMIP5 simulations of the EC-EARTH GCM. The 30-year SCM simulations are performed at two cfSites of interest, each site representing a different climate regime. The Barbados Cloud Observatory (BCO) reflects subtropical marine Tradewind conditions, while the Cabauw site (CESAR) in the Netherlands frequently features mid-latitude continental boundary layer clouds. A key novelty compared to previous SCM climate studies such as CGILS is that the prescribed large-scale forcings are non-idealized as well as highly variable in time. As a result, artificial grid-locking effects are automatically avoided; in addition, the forcings can be made representative of different scenarios of future climate. This enables the targeted use of SCM simulation as a laboratory for investigating the response of boundary layer clouds in GCM. The results of this study provide support for such use of long-term SCM as a climate feedback testbed, and provide some guidance on how large-eddy simulations and high-frequency observations can be integrated into this framework.
Abstracts

Daleu, Chimene Laure

University of Reading
c.daleu@reading.ac.uk

Intercomparison of methods of coupling between convection and large-scale circulation.

In the past decade, a set of methods of parameterizing large-scale dynamics has offered a computationally cheap way to study a range of problems in which two-way interactions between tropical convection and large scale dynamics are essential. One of the methods, the weak temperature gradient (WTG) approximation is to derive the large-scale circulation from the assumption that its action counteracts the local buoyancy anomaly and thus, maintains the horizontal variations of potential temperature close to zero. Another method, the damped-gravity wave (DGW) is to derive the large-scale circulation directly from the momentum equation. Much insight has been learned from such studies but however, both agreement and discrepancies between different studies are seen in the published results. The GASS-WTG international intercomparison project has been initiated in early 2014. The project aims to compare the WTG and DGW methods with a consistent implementation in a number of CRMs and SCMs, and to compare the behaviour of a number of CRMs and SCMs under consistent parameterizations of the large-scale dynamics. For each model, the implementation of the WTG or DGW method involves a simulated column which is coupled to a reference state. The reference state is defined with profiles obtained from the same model in radiative-convective equilibrium. In Part I, the simulated column has the same sea surface temperature (SST) as the reference state. In Part II, the reference state is held fixed while the SST of the simulated column is varied. Here, we are presenting some of the main differences that have emerged between the models and methods. For both uniform and non-uniform SST conditions, SCMs display a wider range of behaviours than CRMs. CRMs show a fairly linear relationship between precipitation and circulation strength. Within an individual SCM, a DGW simulation and a corresponding WTG simulation can produce different signed circulation. The DGW simulations produce large-scale pressure velocity profiles which are smoother than and less top–heavy compared to those produced by the WTG simulations. Over uniform SST, only a few models reproduce their own reference solutions, while others sustain a large-scale circulation which results in either substantially lower or higher precipitation compared to the value of the reference state. Some SCMs under the WTG method produce zero precipitation. When initialized with a dry troposphere, DGW simulations always result in a precipitating equilibrium state. The greatest sensitivities to the initial moisture conditions occur for multiple stable equilibria in some WTG, corresponding to either a dry equilibrium state when initialized as dry or a precipitating equilibrium state when initialized as moist. In some models, the existence of multiple equilibria is sensitive to some parameters in the WTG calculations. Over non-uniform SST, a large proportion of models shows a non-linear increases of precipitation with the SST. F
Dauhut, Thibaut

University of Toulouse & CNRS

thibaut.dauhut@aero.obs-mip.fr

Giga-LES of Hector the Convector keeping the tallest updrafts almost undiluted on their way to the stratosphere

The hydration of the stratosphere by Hector the Convector, observed on 30 November 2005 over the Tiwi Islands, Australia, is investigated using a Giga Large-Eddy Simulation with a 100-m cubic mesh. Individual updrafts defined as 3D objects with vertical velocity above 10 m/s are identified. Among the 20000 updrafts identified during the most intense phase, a dozen was more-than-4-km tall. The two tallest account for 50 to 70 % of the total updraft volume. Their locations were determined by low-level convergence lines first created by the sea breeze in the morning, then enhanced by cold pools due to congestus and finally reinforced each other as they moved inland and intersected. The two tallest updrafts that overshot the stratosphere were contrasted with those occurring one hour earlier and later. They present larger width (up to 8 km), greater equivalent potential temperature (10 to 30 K larger than the environment), stronger vertical velocities (up to 50 m/s) and larger hydrometeor contents (more than 10 g/kg). They kept their core almost undiluted on their way to the stratosphere with an entrainment rate as low as 0.08 /km. Both the low-level convergence lines intensified by cold pools and the reduced mixing in the troposphere are found to be determinant for the transition from deep to very deep convection. This study was supported by the StratoClim project.
Deluca Silberberg, Anna

*MPI for the Physics of Complex Systems*

adeluca@pks.mpg.de

**Understanding the Transition to Strong Convection in Realistic and Idealised Cloud-Resolving Simulations of Different Aggregation Scenarios**

Recent empirical studies across a broad range of observational scales have attempted to characterize aspects of convective phenomena with a view to constraining convective parametrizations. In particular, some of them have tried to connect convective organization with theories of critical phenomena and statistical physics. In this contribution, we analyse, from the perspective of critical phenomena, idealised and realistic runs of the Met Office Unified Model. The idealized run is 4km with a squared domain lateral size of 576 km with periodic lateral boundary conditions and 40 days with 3D Smagorinsky mixing and explicit convection. The other cases are real studies of organized convection with different level of aggregation with domains in the Indian ocean and the West Pacific ocean around the equator with lateral boundaries forced from ECMWF analyses. Our study focuses on, on the one hand, the relationship between water vapour, precipitation and rainfall extremes. This transition is still not well characterized and previous work have found contradictory results between real data and models, as well as for different water vapour observables. We find differences between idealized and realistic runs with different aggregation levels. We try to explain such findings and investigate the effects of observational uncertainties in these relationships. On the other hand, we look at different statistical properties of clouds and precipitation, such as the energy distribution of convective clusters and study its scaling properties in time and space including any dependence in the state of aggregation of the run. Note: This work is a collaboration of Dr. Plant and Dr. Holloway from the University of Reading together with Dr. Deluca and Prof. Kantz from the Max Planck Institute from the Physics of Complex Systems. This findings have not been yet published.
Denby, Leif

University of Cambridge

lcd33@cam.ac.uk

Exposing entrainment with high-resolution modelling

The effect of clouds is the single most uncertain contribution to current climate change predictions. 30% of the uncertainty in climate sensitivity has been directly attributed to the poorly constrained parameterisation of entrainment of ambient air into convective plumes. There is therefore an urgent need to improve parametrisation of convective cloud activity. In this talk, I will present a new description of entrainment that has been constrained by using a novel method for entrainment analysis of high-resolution (10m) simulations of individual convective clouds. In particular I will focus on how the effects of windshear can be included into the entrainment parameterisation, which is not considered in any operational models. I have developed a new 1D entraining parcel-model which is implemented in the Convective Cloud Field Model (CCFM) convection parameterisation. CCFM is an ideal host for a better entrainment description as it uses a 1D model of individual convective clouds in explicitly resolving a spectra of cloud sizes, avoiding the use of a bulk-parameterisation description of entrainment. With the improvements to entrainment in the 1D cloud model CCFM shows significant improvements in capturing the diurnal cycle of precipitation and the large-scale precipitation bias in the tropics.
A downscaled METEOSAT SEVIRI cloud properties dataset based on the high-resolution visible channel

The geostationary meteorological imager METEOSAT SEVIRI offers a unique view on the temporal evolution of cloud over Europe, which makes it the instrument of choice for studying their life cycle. Information on small-scale cloud structures are however limited by its relatively coarse nadir spatial resolution of 3x3km². In particular, this resolution does not allow to properly resolve shallow convective clouds, which are of high relevance for the climate, and are still poorly represented in atmospheric models. Within the project High Definition Clouds and Precipitation for advancing Climate Prediction, a unique cloud dataset has been developed which for the first time provides cloud properties at the spatial resolution of SEVIRI’s High-Resolution Visible channel, with a nadir resolution of 1x1km². It thereby achieves a significant step towards resolving clouds at the convective scale, and is based on the statistical downscaling of spectral radiances, and includes an estimate of the uncertainties incurred by the downscaling. The aim of this presentation is to introduce this dataset to potential users, highlight some applications, and show a comparison of the dataset to SEVIRI standard resolution products together with collocated MODIS measurements to illustrate the benefits of this dataset.
Di Girolamo, Paolo

University of Basilicata
digirolamo@unibas.it

Characterization of Turbulent Processes by Raman Lidar System BASIL

Authors’ list: Paolo Di Girolamo, Donato Summa, Dario Stelitano, Marco Cacciani, Andrea Scoccione, Andreas Behrendt, Volker Wulfmeyer

Measurements carried out by the Raman lidar system BASIL are reported to demonstrate the capability of this instrument to characterize turbulent processes within the convective boundary layer. In order to resolve the vertical profiles of turbulent variables, high resolution water vapour and temperature measurements (10 sec, 30-90 m) are considered. Measurements of higher-order moments of the turbulent fluctuations of water vapour mixing ratio and temperature are obtained based on the application of spectral and autocovariance analyses to the water vapour mixing ratio and temperature time series. The algorithms are applied to a case study (20 April 2013) from the (HD(CP)2) Observational Prototype Experiment. The noise errors are small enough to derive up to fourth-order moments for both water vapour mixing ratio and temperature fluctuations. For the considered case study, which represents a well-mixed and quasi-stationary CBL, the mean boundary layer height is found to be 1290±77 m a.g.l. Values of the integral scale for water vapour and temperature fluctuations at the top of the CBL are in the range 80-100 s and 40-115 s, respectively, much larger than the temporal resolution of the measurements (10 s), which testify that the temporal resolution considered for the reported measurements is sufficient to resolve the major part of the turbulent fluctuations. Peak values of all moments are found in the interfacial layer in the proximity of the top of the CBL. Specifically, the water vapour and temperature variance has a maximum value of 0.29 g2kg-2 and 0.37 K2, respectively, the water vapour and temperature third-order moment has a peak value of 0.156 g3kg-3 and -0.11 K3, respectively, while water vapour and temperature fourth-order moment has a maximum value of 0.28 g4kg-4 and 0.36 K4. Results obtained in this study will be discussed in detail at the Conference.
Diedrich, Hannes

Free University Berlin

hannes.diedrich@wew.fu-berlin.de

A Study on the Relation Between Clouds Properties and Total Column Water Vapour from Space- and Groundbased Observations

In the course of the evaluation of the accuracy of our new universal Satellite retrieval for Total Column Water Vapour (TCWV) that is only valid for cloud free scenes, we studied the relationship between TCWV and cloud properties. TCWV, derived from satellite measurements, is used to evaluate Numerical Weather Prediction (NWP) models or serves climate monitoring. Additionally, the interaction between water vapour and clouds is an important factor for cloud formation and precipitation. We combined a TCWV data set from GPS measurements over Germany, that is not affected by clouds, with the well established Level-2 cloud product of the Moderate Resolution Imaging Spectroradiometer (MODIS). These observations were collocated with outputs from NWP model data of COSMO-DE and ERA interim. In the presentation we will show statistics of TCWV, cloud water path, cloud phase, cloud cover and other cloud properties for the years 2008-2012 for both observations and models. These studies can help to improve the cloud parametrizations of the models e.g. the probability density functions of sub-grid water vapour variability in cloudy situations, which in turn will improve the computation of radiative fluxes, precipitation forecasts etc.
Donovan, David

KNMI
donovan@knmi.nl

An Overview of the Scientific Aspects of the Earth Clouds and Radiation Explorer (EarthCARE) Mission

D.P. Donovan and the members of the EarthCARE Mission Advisory Group

The value of multi-sensor remote sensing applied to cloud, aerosol, radiation and precipitation studies has become clear in recent year. For example, combinations of instruments including passive radiometers, lidars and cloud radars have proved invaluable for their ability to retrieve profiles of cloud macrophysical and microphysical properties. This is amply illustrated by various results from the US-DoE ARM (and similar) surface sites as well as results from data collected by sensors aboard the A-train satellites CloudSat, CALIPSO, and Terra. The Earth Clouds Aerosol and Radiation Explorer (EarthCARE) mission is a combined ESA/JAXA mission set for launch in 2018 and has been designed with sensor-synergy playing a key role. The mission consists of a cloud-profiling radar, a high-spectral resolution cloud/aerosol lidar, a cloud/aerosol imager, and a three-view broadband radiometer (BBR) covering both LW and SW bands. The mission will deliver cloud, aerosol and radiation products focusing on horizontal scales ranging from 1 km to 10 km. EarthCARE data will be used in multiple ways ranging from cloud-aerosol model evaluation studies, to GCM-orientated cloud microphysical property parameterization development, to radiative closure studies, and even data assimilation activities. By using innovative methods of combining the 2-D vertical properties retrieved along the nadir lidar/radar view with the 2-D horizontal context provide by the imager, EarthCARE will be able to deliver level-2 products which will, thanks to BBR data, have already been evaluated for radiative consistency. In this presentation, a brief overview of EarthCARE mission will be given, describing the scientific motivation of the mission and highlighting the planned synergetic use of EarthCARE data.
A Novel depolarization lidar technique for the retrieval of liquid water cloud properties.


The links between multiple-scattering induced depolarisation and cloud microphysical properties (e.g. cloud particle number density, effective radius, water content) have long been recognised. Previous efforts to use depolarisation information in a quantitative manner to retrieve cloud microphysical cloud properties have also been undertaken but with limited scope and, arguably, success. In this work we present a depolarization lidar retrieval procedure for LWC, number density and effective particle size. The procedure is applicable to liquid clouds with (quasi-)linear LWC profiles and (quasi-)constant number density profiles in the cloud-base region. This set of assumptions allows us to employ a fast and robust procedure based on a look-up-table approach applied to extensive polarization lidar Monte-Carlo multiple-scattering calculations. Example validation cases are presented where the results of the inversion procedure are compared with simultaneous cloud radar observations. In non-drizzling conditions it was found, in general, that the lidar-only inversion results can be used to predict the radar reflectivity within the radar calibration uncertainty (2-3 dBZ). Results of a 3 month comparison between ground-based aerosol number concentration and lidar-derived cloud base number considerations are also presented. The observed relationship between the two quantities is seen to be consistent with the results of previous studies based on aircraft-based in situ measurements.
Inexact hardware for poor models: The use of reduced numerical precision to achieve maximal resolution in atmospheric modelling

The use of inexact hardware is promising large savings in power consumption and an increase in computational performance. This would allow an increase in resolution in atmosphere models and might be a short-cut to global cloud-resolving modelling. However, simulations with inexact hardware show numerical errors, such as rounding errors or bit flips. In cooperation with groups in computing science we have studied different approaches to inexact hardware in atmospheric simulations. We found that numerical precision can be reduced significantly within simulations of a dynamical core of the three-dimensional atmosphere with no significant degradation in results. We show that model error is increased much stronger if resolution of the double precision setup is decreased, instead of the decrease in numerical precision, to save the same amount of computing power. We will also present preliminary results of a study that is using emulated reduced precision hardware to integrate the cloud-resolving model in a superparametrised atmosphere model. We aim to treat different parts of atmospheric dynamics with customized computational accuracy to reflect their inherent uncertainties. But how can we identify those parts of atmosphere models that can accept a strong reduction in precision? We found that a comparison between the impact of rounding errors and the influence of parametrisation schemes (and in particular stochastic parametrisation schemes) can provide valuable information on the precision that should be used. To go further, we find that the influence of rounding errors can be be beneficial for the representation of sub-grid-scale variability. We believe that the use of inexact hardware will allow significant improvements of atmosphere models in the future if it is realised in a close cooperation between computing scientists and model developers to represent uncertainties correctly and to achieve maximal performance and resolution.
Düsing, Sebastian

TROPOS
duesing@tropos.de

Vertical distribution of CCN and aerosol particles during HOPE Melpitz and the comparison with Lidar measurements

The HOPE-Melpitz campaign was performed within the scope of HDCP2 in Melpitz, Germany in September 2013. The microphysical properties of aerosol particles, such as particle number size distribution (PNSD), cloud condensation nuclei (CCN) number concentration and meteorological parameters, like temperature, relative humidity, wind direction and speed were measured using the helicopter-borne platform ACTOS with a high temporal and spatial resolution operated with a true air speed (TAS) of 20 m s\(^{-1}\) in heights up to 2500 m. Using these data, vertical profiles of size-resolved particle number concentrations as well as CCN concentrations can be derived and answer the question under which conditions ground-based data might be representative for the boundary layer.

A second question was how well do continuously available remote sensing data agree with in-situ “snapshot” measurements. To compare these data optical properties of the aerosol under ambient conditions were calculated using in-situ data and a modified MIE-model based on the core-shell (CS) mixing state assumption. Therefore the hygroscopic growth factor and the refractive index of the aerosol particles was needed and were taken from CCN data and chemical composition, both measured on ground. The optical properties of the aerosol were measured for three wavelengths (355, 532, 1064 nm) with the POLLYXT lidar system continuously and were compared with the calculated values in particular the aerosol backscatter coefficient $\beta$ [Mm$^{-1}$] for different heights within and above of the planetary boundary layer (PBL). For the red channel of the LIDAR (1064 nm) the backscatter coefficients agree within the uncertainties in 8/9 cases, in 4/10 cases for the green (532 nm) channel and for the blue channel (355 nm) in 50% of the cases.
Ebell, Kerstin

University of Cologne

kebell@meteo.uni-koeln.de

The complexity of a 1D-Var retrieval for temperature, humidity and warm clouds

Warm clouds, consisting of liquid droplets only, are assumed to be the simplest cloud type to be observed. However, retrieved warm cloud properties, i.e. liquid water content and droplet effective radius, may differ significantly among different retrieval methods. Uncertainties may arise from retrieval assumptions but also from measurement biases. Here, we will present the results of a 1D-Var retrieval method, the Integrated Profiling Technique (IPT, Löhner et al., 2008), which combines ground-based microwave radiometer (MWR), cloud radar and a priori information to derive profiles of temperature, humidity, liquid water content (LWC) and droplet effective radius (REF). In contrast to other commonly used cloud radar-MWR-methods, which retrieve LWC and REF from simple relations (e.g. Frisch et al., 1995, 1998), the IPT provides physically consistent profiles implying that the measurements can be reproduced from the retrieved profiles within their assumed errors. First, we will test the retrieval performance using synthetic observations. Knowing the "truth", i.e. the true T, q, LWC, and REF profiles, we can simulate what the instruments would observe. In this way, we can test how the retrieval behaves under ideal conditions. Ideal means that no (often unknown) instrument biases exist and the forward model and the corresponding assumptions in the forward model are appropriate. On the one hand this approach allows to test if the retrieval and its equations have been set up properly, on the other hand it allows to analyze the interplay of prior, measurement and forward model uncertainties in the retrieval. In the "real world", it is likely that measurements are biased due to calibration errors or drifts in the instrument. Furthermore, the forward model might not be appropriate; e.g. the droplet size distribution assumed in the forward model might not represent the true one. We will also assess how such discrepancies affect the retrieved cloud property profiles. In addition, the application of the IPT to the cloud observations at the Jülich Observatory for Cloud Evolution (JOYCE) and the Richard Aßmann Observatory (RAO) will be presented. The results will also be set into context to other commonly used cloud radar - MWR cloud retrieval algorithms.
Fläschner, Dagmar

Max Planck Institute for Meteorology
dagmar.flaeschner@mpimet.mpg.de

A theoretical framework to understand inter-model differences in regional precipitation patterns

Regional precipitation change is uncertain among state-of-the-art general circulation models. The deviating precipitation response even persists when reducing the model experiment complexity to aquaplanet simulation with forced sea surface temperatures (Stevens and Bony, 2013). Voigt and Shaw (2015) attribute the model disagreement to cloud and water vapor radiative effects. Their results suggest, however, that inter-model differences remain in the precipitation pattern change even with disabled cloud radiative effects. The seed for inter-model differences may be present in the absence of clouds. To investigate the potential seed for different precipitation patterns we analyze data from 6 general circulation models performing the aquaplanet simulations of the Clouds On Off Klima Intercomparison Experiment (COOKIE), where clouds are transparent to radiation. Although cloud radiative effects are then disabled, the precipitation patterns among models are as diverse as with cloud radiative effects switched on. We develop a theoretical framework to understand inter-model differences in tropical precipitation patterns. The framework evolves from the moist static energy budget and connects atmospheric heating and the atmospheric stability to the vertical velocity. Through the relationship of precipitation and vertical velocity, precipitation patterns can be reconstructed. The framework thus allows testing for separate influences of heating and stability on inter-model differences of precipitation patterns. With the help of this framework we investigate likely causes for the disagreement among models. References Stevens, B. & Bony, S.: What Are Climate Models Missing?, Science, 2013, 340, 1053-1054 Voigt, A. and Shaw, T. A.: Circulation response to warming shaped by radiative changes of clouds and water vapour, Nature Geosci, 2015, 8, 102-106
Microphysics Matters: A Global Perspective

Microphysics is about the small scale, but the impacts are global. From the cloud scales of turbulent motion down to the molecular scales of particle interactions, weather prediction and climate models must parametrize these subgrid scale processes. The accuracy of the parametrizations has huge implications for radiation, for dynamics and for the hydrological cycle. This talk will provide an overview of recent developments and challenges for cloud microphysics parametrization in global NWP and climate models, discussing the level of complexity we need to capture, and the continuing uncertainties that we face. A few examples from the ECMWF global model will highlight the importance of improving the representation of microphysical processes, such as the effect of supercooled liquid water in high-latitude cloud systems on large-scale radiation biases. There is much potential to make further progress, making novel use of observations and turbulent resolving simulations to inform parametrizations for the larger-scale models.
Continuous Water vapour profiles from within and above a cloud from ground-based remote sensing

Raman lidars (RL) enable a precise observation of tropospheric water vapour profiles during clear sky conditions. However, in the presence of clouds only profiles up to cloud base are available. In contrast, a microwave radiometer (MWR) provides water vapour profiles during all non-precipitating conditions, but with coarse vertical resolution. Therefore, uninterrupted and continuous water vapour profile observations are challenging. We present a method to derive a continuous time series of water vapour profiles from a combination of ground-based remote sensing techniques. During HOPE in spring 2013 a variety of instruments were installed at supersites which provided excellent data for this approach. We developed a two-step algorithm combining the RL mass-mixing ratio and MWR brightness temperatures. The first step is a Kalman filter that expands the RL water vapour profiles to the full height range. In the second step, these filtered profiles serve as input to the one-dimensional variational retrieval that optimally estimates the profiles. With this technique we are able to retrieve reliable water vapour profiles and the associated errors on a routine basis even from inside and above a cloud during all weather conditions except for rain. In a statistical analysis we contrast the retrieved profiles to radiosondes, models and other remote sensing products during HOPE. Based on this statistics we illustrate limitations and advantages of the presented retrieval. An application to long term data sets is intended, as well as an implementation to the CLOUDNET data processing.
Gantner, Leonhard

IMK, Karlsruhe Institute of Technology

leonhard.gantner@kit.edu

The impact of land-surface parameter resolution on cloud-topped CBLs

Land surface parameters such as land use as well as soil characteristics influence the state of the CBL and the formation of clouds by determining the partitioning of the available energy into turbulent fluxes of sensible and latent heat. With the availability of more powerful computers the horizontal resolution in atmospheric models continues to increase. As horizontally better resolved land surface parameters become available as well, the question arises as to what extent the horizontal resolution of the land surface parameters influences the CBL and clouds. For our runs vegetation and soil information is taken from standard datasets. Soil moisture and temperature is generated by offline runs of the SVAT model TERRA driven by radar measurements of precipitation. In our study we run the COSMO model in LES mode with 0.001° (100 m) grid point distance. Compared with the operational version, using 0.025° grid point distance we achieve a higher and more realistic horizontal variation of the surface fluxes in our control run. By varying the resolution of the underlying land surface parameters, which are soil properties, soil moisture and land use, we investigate their effect on the CBL and low-level cloud formation. We performed sensitivity runs, where we averaged land surface parameters over areas with 25x25, 100x100 grid boxes and the whole computing domain. We will show the effect of the lower resolved land surface parameters on CBL clouds and the vertical profile of areal mean values of variables like temperature, moisture and wind in the CBL as well as their standard deviation.
Gerard, Luc

RMIB

luc.gerard@meteo.be

Perturbation approach for scale-aware convection parameterization at kilometer resolution.

In a model with grid spacing finer than 10 km, the convective systems influence the mean grid-box values; the convective circulations are partly resolved and the convective condensation produces a signal in the statistical cloud scheme. As long as the model grid is not fine enough to completely resolve the convection, the subgrid convection parameterization should produce a complement to these resolved signals. It must take into account that the mean grid box conditions no longer represent the convective cloud environment that could be observed in the real world, while the subgrid ensemble becomes too small to assume a steady state. The complementary subgrid draught parameterization (Gerard 2015) represents a perturbation-updraught circulation, closed in the same model column, and accounting for the convective mesh fraction. Prognostic variables allow a gradual evolution in time of the subgrid ensemble. The closure is specific for the perturbation-updraught, further helping scale awareness. The formulation of the triggering and the use of a specific triggering criterion were also found important issues. The performance of the scheme has been assessed in the operational limited-area model Alaro. The scheme is able to produce a smooth transition from mostly parameterized to mostly explicit representation of the convective phenomena. We will present the main features, compared results when varying the model resolution from a few tens km to 1-km grid spacing, and sketch ways for further improvement.
Goecke, Tobias

*DWD*

tobias.goecke@dwd.de

**Tendency perturbations from high-resolution model data**

Low resolution models are known to poorly describe the propagation and growth of small scale errors from e.g. uncertainty in initial conditions due to the inability to resolve small scale processes. Understanding the mechanisms and rates of error growth in highly resolving models is a step towards a successful parametrization of uncertainty. Utilizing the HDCP2/ICON-LES model output we obtain pdf's of the tendencies of prognostic variables on the sub-kilometer scale. This facilitates the derivation of a stochastic force to be used in parametrizations in order to describe a realistic error growth.
Gorodetskaya, Irina

KU Leuven

irina.gorodetskaya@ees.kuleuven.be

Exploiting high resolution ground-based and space-borne remote sensing to evaluate precipitation estimates from regional climate models in Antarctica

Precipitation is the major positive component of the Antarctic ice sheet surface mass balance (SMB). However, estimating the contribution of precipitation to the ice sheet SMB is hindered by the difficulty and near absence of long-term precipitation measurements. A vertically profiling 24-GHz precipitation radar MRR has been installed as part of the unique cloud-precipitation-meteorological observatory at Princess Elisabeth (PE) base in Dronning Maud Land (DML), East Antarctica, allowing to assess contribution of the snowfall to the local SMB and comparing it to other SMB components. Snowfall rate (S) is derived from the radar’s effective reflectivity factor (Ze) at 400 m agl using various Ze-S relationships for dry snow. Snowfall occurred during 17 % of the cloudy periods with a predominance of light precipitation and only rare events with snowfall > 1 mm h\(^{-1}\) water equivalent (w.e.). These occasional large precipitation events contribute most to the yearly snow accumulation. Year-long radar measurements at PE during 2012 showed annual total snowfall amount of 110±20 mm w.e. of which only 53±10 mm w.e. accumulated on the ground. Snow sublimation (surface and drifting snow) and snow erosion by the wind removed 23% and 30% of the precipitation input, accordingly. Radar precipitation measurements at PE are used to evaluate two regional climate models - RACMO2 and MAR - simulating DML climate at 5-km horizontal resolution. Particular precipitation events are evaluated using the Passive and Active Microwave TRAnsfer model (PAMTRA), which allows direct comparison of the radar-measured and model-based vertical profiles of the radar reflectivity and Doppler velocity. The 1D profile comparison is complemented by the analysis of spatio-temporal precipitation patterns in the models and derived from the CloudSat radar. The combination of ground-based and satellite remote sensing with regional climate modeling allows for a process-based model evaluation and process understanding.
Görsch, Norman

DLR - IPA

norman.goersch@dlr.de

The Lagrangian diagnostic tool "LaMETTA" for ICON/MESSy

The Lagrangian MESSy Tool for Trajectory Analyses (LaMETTA) provides the framework for on-line diagnostics within ICON from the Lagrangian perspective. The potentially vast number of trajectories used during runtime can be further analyzed by additional submodels coupled through MESSy to LaMETTA. The poster provides an introduction into the technical implementation and the use of LaMETTA. To offer a high flexibility, most options can be controlled through namelists, e.g., the choice of numerical methods for interpolation and advection, or the ICON-variables to be interpolated onto the trajectories. Derived information, for example place and time of the recent surface contact of a trajectory, can be computed within custom-built submodels and stored together with the trajectories positions. An example on how to couple such a submodel via MESSy to LaMETTA is also shown.
Towards global large eddy simulation: super-parameterization revisited

This talk will present the case for a global large eddy simulation model applying the super-parameterization (SP) methodology on massively parallel computers. I proposed SP about 15 years ago to improve representation of deep convection and accompanying cloud processes in large-scale models of weather and climate. The main idea behind SP is to embed---in all columns of the large-scale model with a horizontal gridlength of the order of 100 km---copies of a two-dimensional nonhydrostatic convection-permitting small-scale model with about 1 km horizontal gridlength and periodic lateral boundary conditions, and to couple them with the outer model. This methodology can be expanded by applying a high-spatial-resolution three-dimensional SP model, essentially a large-eddy simulation model, and by embedding its copies in all columns of a large-scale model with the horizontal gridlength in the range of 10 to 50~km. The outer model will then simulate processes down to the mesoscale (e.g., organized convection) and small-scale processes (e.g., boundary layer turbulence, convective drafts) will be simulated by LES models. Although significantly more expensive than the traditional SP, the SP LES is ideally suited to take advantage of parallel computers (e.g., applying GPU technology) because of the minimal communication between LES models when each processor runs a single LES model. Additional benefits of such a methodology will be discussed, and a simple computational example will be presented.
Grant, Leah

*Colorado State University*

ldgrant@atmos.colostate.edu

**Modeling cold pool – surface flux interactions**

Cold pools are ubiquitous in the atmosphere, and their important roles in deep convective initiation and organization are well known. Cold pools can modulate surface sensible and latent heat fluxes, and in turn, surface fluxes may modify cold pools and their potential to initiate convection. The two-way interaction between cold pools and surface energy fluxes has not yet been investigated in detail. The goal of this study is therefore to understand the mechanisms by which surface fluxes, both within the cold pool and in the surrounding environment, modify the characteristics of cold pools. This goal is accomplished using high-resolution (grid spacings as fine as 10 m), idealized, 2D simulations of isolated cold pools. In the proposed experiments, the surface flux formulation, surface type, and environmental conditions are systematically varied from tropical oceanic to dry continental. Additionally, two other sets of experiments are performed for a subset of the 2D experiment suite: (1) the grid spacing is coarsened to determine at what resolutions cold pool – surface flux interactions are adequately captured; and (2) several 3D simulations are performed in order to evaluate the 2D results. The impact of surface fluxes on cold pool characteristics, including the buoyancy, maximum vertical velocity, and moisture distribution, are analyzed and will be presented. The results suggest that the mechanisms by which surface fluxes and cold pools interact vary substantially with the environment. Additionally, the indirect effects of surface fluxes on turbulent entrainment rates into the cold pool are found to play an important role in cold pool evolution. These results suggest that surface fluxes can impact the timing and manner in which cold pools initiate convection, and that their effects may be important to incorporate into cold pool parameterizations for climate simulations.
Grell, Evelyn

CIRES, NOAA/ESRL/PSD
Evelyn.Grell@noaa.gov

A Revisit of the Interaction between Microphysical Processes and Flow Dynamics over Meso-beta Ridges: Microphysics Budget Analysis

This study focuses on using microphysics budget analyses to investigate the interaction between microphysical processes and flow dynamics over meso-beta ridges. High resolution simulations of the Weather Research and Forecasting Model (WRF) are carried out using four commonly-used microphysics schemes including one-moment and two-moment bulk schemes with two different horizontal grid spacings: $\Delta x = 4$ and $1$ km (with identical vertical grids). Diagnoses of the source and sink terms of the hydrometeor budget equations reveal the fundamental differences in parametrized microphysical processes that contribute to the difference in the simulated latent-heat-induced reduction of windward-side blocking and the enhancement of leeward-side precipitation spillover. The results from the microphysics budget analysis also show a comprehensive sequence of events in the interaction of individual microphysical processes and atmospheric dynamics.
Grell, Georg

NOAA/ESRL/GSD

georg.a.grell@noaa.gov

Aerosol awareness in a convective parameterization for deep and shallow convection: Comparison to cloud resolving simulations

A convective parameterization is applied and evaluated that may be used in high resolution non-hydrostatic mesoscale models for weather and air quality prediction, as well as in modeling system with unstructured varying grid resolutions and for convection aware simulations. This scheme is based on a stochastic approach originally implemented by Grell and Devenyi (2002) and described in more detail in Grell and Freitas (2014, ACP). It was expanded to include PDF’s for vertical mass flux in deep and shallow convection, and additional closures and aerosol dependence in the shallow scheme. Interactions with aerosols have been implemented through a CCN dependent autoconversion of cloud water to rain as well as an aerosol dependent evaporation of cloud drops. Initial tests with this newly implemented aerosol approach showed plausible results with a decrease in predicted precipitation in some areas, caused by the changed autoconversion mechanism. Here we compare and evaluate performance over a 10-day period using the SAMBBA test case of the Working Group for Numerical Experimentation (WGNE) on aerosol impacts on numerical weather prediction. A shorter period is also compared to fully cloud-resolving simulations using WRF-Chem.
Grützun, Verena

University of Hamburg

verena.gruetzun@uni-hamburg.de

Comparing coarse grid data with long-term measurements from supersites – challenges and opportunities

Verena Grützun, Shengyin Li, Felix Ament, Stefan Bühler

The evaluation of gridded domain data from models or satellites with point measurements is a challenging task. Ideally we would have data, which is highly-resolved in space and time and is thus representative for the grid box or satellite footprint which we would like to evaluate. However, such highly-resolved data is not available and we have to trade spatial resolution versus time resolution or horizontal coverage against height resolution. Even the comparison of two highly resolved data sets from model and ground based data bears challenges, since atmospheric models are normally not able to simulate for example the correct location of convective cells. We explore the potential of long time series from supersites and horizontally highly-resolved observation data to e.g. evaluate the new satellite cloud ice product SPAREICE or to estimate distribution parameters for cloud variables in models.
In order to quantify the aerosol impact on ice cloud microphysics, aerosol specific parameterisations for immersion freezing and deposition nucleation have been developed and applied to models. However contact nucleation has been largely treated as aerosol independent due to the lack of quantitative laboratory measurements. Here we present a new parameterisation for contact nucleation, which combines theoretical collision efficiency calculations with recent experimentally determined freezing efficiency data. Unlike previous parameterisations which are only temperature dependent, the new parameterisation includes dependencies on aerosol and cloud droplet physical properties. The results indicate that the aerosol physical properties play a significant role in determining the concentration of ice nucleating particles in the contact mode. A comparison between the immersion, deposition, and contact parameterisation shows that under certain conditions, contact nucleation is an important process in determining the concentration of ice nucleating particles. This is further investigated by applying the three different ice nucleation parameterisations to the COSMO model. A semi idealised convective cloud was simulated at very high resolution of 100m, and the relative importance of the different ice nucleation mechanisms was quantified.
Hanley, Kirsty

Met Office

kirsty.hanley@metoffice.gov.uk

Simulating convective storms in the Unified Model at 1.5 km to 50 m gridlength

Convective storms are a crucially important forecasting problem in the UK, not least because of the flooding they can cause. In the last few years many operational weather centres have begun to run at “convection permitting” resolutions, with the UK Met Office currently running a 1.5 km forecast model. While there is evidence that precipitation forecasts at this grid length are more accurate than lower resolution forecasts, it is clear that there are still significant shortcomings in the nature of the simulated convective cells. Cells in the model tend to be too large and too intense, and tend not to organise into Mesoscale complexes as observed, indicating that convection is not fully resolved at this grid length as well as illustrating our lack of understanding of the nature of small-scale mixing and microphysical processes. The DYMECS (Dynamical and Microphysical Evolution of Convective Storms) and COPE (COnvective Precipitation Experiment) projects provide a large database of observations of convective storms that can be used to evaluate NWP models. In this study we perform simulations of some of the DYMECS and COPE cases with the Met Office Unified Model (UM) at horizontal grid lengths ranging from 1.5 km to 50 m, which allows us to apply a statistical approach to evaluate the properties and evolution of the simulated storms over a range of conditions. Here we present results comparing the storm morphology in the model and reality which show that the simulated storms become smaller as grid length decreases and that the grid length that fits the observations best changes with the size of the observed cells. We also show that the modelled storm morphology is very sensitive to some aspects of the model configuration, such as the subgrid mixing scheme.
Hansen, Akio

University of Hamburg

akio.hansen@uni-hamburg.de

Model evaluation by a virtual Cloudnet supersite based on forward operators

Novel validation techniques are essential for the detailed evaluation of the high resolution HD(CP)$^2$ simulations to enhance parameterizations and the ICON model itself. Especially for the evaluation of cloud’s representation, the cloud target classification, developed by Cloudnet, is one of the most useful observational products. The cloud classification is based on the Cloudnet algorithms and is a powerful tool for the detailed analysis of cloud’s structure, type and development. The algorithms differentiate between 11 categories like “ice” or “cloud droplets only”. As a physical consistent counterpart for the model simulations, we’ll present a new “Model to Obs to Cloud Classification” approach. The cloud classification algorithms need observations of an active cloud radar, a LiDAR and a passive microwave radiometer, which together form a Cloudnet supersite. For the model, there is no comparable output available. That’s why different forward operators are used to simulate a virtual and physically consistent Cloudnet supersite with all the above stated instruments. The generated synthetic measurements can be directly compared with the observations by using instrument’s quantities. Nevertheless, the indirect interpretation of model’s shortcomings in terms of observables is not straightforward. Therefore, exactly the same Cloudnet algorithms can be applied on the virtual and on the real measurements to create a consistent cloud classification for the model as well as for the observations. This very valuable synergist product, combining active and passive measurements, enables for an extensively evaluation of cloud’s representation within the model. The novel “Model to Obs to Cloud Classification” approach is applied on the HD(CP)$^2$ ICON LES simulations and compared to the HOPE measurements performed during April and May 2013. First results of the evaluation of cloud’s representation are shown. Moreover first analysis of the uncertainty of the forward operators are presented.
High-resolution WRF/chem simulations to understand the impact of aerosols on ice microphysics in convective clouds

The impact of aerosols on ice- and mixed-phase processes in convective clouds remains highly uncertain, which has strong indications for estimates of the role of aerosol-cloud interactions in the climate system. The wide range of interacting microphysical processes are still poorly understood and often not sufficiently resolved in global climate models. We use cloud-resolving model simulations to directly investigate the microphysical processes controlling the evolution of convective clouds and their susceptibility to changes in aerosol. We have implemented the HAM aerosol model, currently used in the global climate model ECHAM, into WRF/Chem. Furthermore, we perform a detailed aerosol and cloud microphysical pathway analysis to provide insight into the relevant process rates controlling aerosol-cloud interaction, such as the activation of different types of aerosols and effects on hydrometeor partition, latent heating, fall speeds and convective updrafts. By using two double-moment cloud microphysics schemes, we show strong effects of the choice of microphysical parameterization on the representation of ice microphysics in the simulations. We simulate a case study for a large field campaign focussed on mid-latitude convection at the ARM SGP (Southern Great Plains) measurement site. Extensive ground based radar and lidar observations as well as in-situ measurements are used to constrain and evaluate the aerosol and cloud microphysical processes in the simulations. The results underline the importance of an advanced understanding and representation of ice-phase microphysics to represent the effects of aerosol perturbations on convective clouds in models.
Forcing large eddy simulations with mesoscale model output – evaluation by means of observations

Large-eddy simulation (LES) models are used to study atmospheric boundary layer flows with rather idealized boundary conditions. However, more realistic turbulence fields are of great interest for example for parameterization development. To make a step towards less-idealized flows, processes occurring on larger scales than those covered by LES have to be considered. Large-scale tendencies are incorporated by coupling LES with mesoscale model output in terms of prescribing advective forcing and applying continuous nudging. This setup provides the opportunity to step from single-day LES case studies to continuous LES of weeks, months and even years. The present work evaluates whether this approach is able to provide a realistic boundary layer representation. Two LES models, PALM and UCLA-LES, are used to simulate a continuous period of 19 days during the observational campaign of the HD(CP)2 (High Definition Clouds and Precipitation for Advancing Climate Prediction) project in April and May 2013 in Jülich, Germany. The simulations are initialized with profiles from analysis data of the mesoscale model COSMO-DE (Consortium for Small-scale Modeling). Time-dependent advective tendencies as well as surface temperature and humidity are prescribed and continuous nudging towards the COSMO data is used to incorporate meteorological forcing. A comparison of turbulence and cloud related statistics with the multi-sensor observations is presented. Sensitivities in terms of chosen averaging domain and temporal resolution of the forcing data and relaxation time scale of the nudging are further explored. The simulated boundary layer depth agrees well with the observations while a correct representation of shallow cloud layers is difficult to achieve. The results depend strongly on the forcing, however, there is a convergence if the averaging domain for the forcing data is large enough. Nudging time scale and higher temporal resolution of the forcing affect the boundary layer development only slightly.
Henneberg, Olga

IAC ETH Zurich

olga.henneberg@env.ethz.ch

Kilometer Scale Simulations of Orographic Mixed-Phase Clouds at a Mountain Range Site

Clouds occurring in a temperature range between 0° C and −38° C may contain supercooled water drops and ice particles formed through heterogeneous freezing. The coexistence of the three water-phases in mixed-phase clouds (MPCs) leads to an enhanced number of microphysical processes that challenges models on every scale. Due to a lower saturation pressure over ice than over water ice growth is favoured and rapid glaciation is expected. Even though MPCs are considered unstable, they have been observed to persist up to several hours. In-situ measurements at the high altitude research station Jungfraujoch (JFJ) show the occurrence and longevity of MPCs under certain wind conditions. Due to the lack of information about updraft velocities in this complex orographic region and the constraint of measurements at a single location it is not fully understood which processes determining the microphysical properties of those MPCs. This requires a detailed model study. The exposed mountain saddle where measurements were taken is challenging for a model study as orography is crucial for MPCs occurrence. The non-hydrostatic model COSMO was used with a 1 km resolution to perform simulations covering the observation campaigns 2012 and 2013 and single cases with changed model set up, treatment of orographic smoothing as well as aerosol conditions. The meteorological parameters like wind and temperature and the many cloud cases observed could be captured and the expected influence of updraft velocities could be constrained by showing moderate mixing ratios during higher vertical velocities and glaciation when velocities were smaller. Simulations with different freezing parametrizations and aerosol concentrations reveal the importance of aerosols competing with dynamics for the formation and longevity of MPCs.
Hernandez-Deckers, Daniel

National University of Colombia, Bogotá
dhernandezd@gmail.com

Are cumulus thermals useful for parameterizing moist convection?

Thermals - small, transient air bubbles - have proved to be useful when taken as the basic convective element in order to investigate cumulus convection dynamics. The thermals' transient nature is a key element that can hardly be depicted by the classical steady plume. Thus, the thermal framework is a good candidate for the development of new convection parameterizations. In order to characterize the dynamics of thermals under different convective regimes, we track thousands of thermals in 3D Large Eddy Simulations using WRF at 65m resolution: two sea-breeze type experiments with different island sizes and one case of daytime convective development over land based on observations from the Large-Scale Biosphere-Atmosphere field study. Overall, thermals are not fundamentally different throughout the different simulations. Their internal vortical circulation is such that they rise much slower than the updraft core speed would suggest, while they mix vigorously with the environment without losing momentum. We find that drag on these thermals is not primarily related to mixing, but rather can be parameterized as standard dissipative drag, proportional to W^2/R. However, this relationship is sensitive to convective intensity: as convection intensifies, the drag coefficient decreases, i.e., thermals become less 'sticky' and more 'slippery'.
Herzog, Michael

University of Cambridge

mh526@cam.ac.uk

The Convective Cloud Field Model: Adding Effects of Wind Shear

The Convective Cloud Field Model (CCFM) is a multi-plume convection scheme. Using an entraining parcel model the scheme calculates possible clouds of different initial radii for a given environment and large scale forcing. The distinctive feature of CCFM is the cloud spectrum calculation which determines the actual number of possible clouds. The spectrum calculation is described by a multivariate Lotka–Volterra system in which clouds (predators) compete for CAPE (convective available potential energy, prey) through their cloud work function. From the individual clouds and their number, mass fluxes and thus convective heating and moistening can be derived. CCFM has been successfully coupled to the ECHAM climate model. Wind shear effects convective plumes through an increase in entrainment. By adding a prognostic equation for the horizontal displacement of the entraining parcel and based on results from lab experiments the effect of wind shear on entrainment can be parameterized within CCFM. Studies of the extended CCFM within ECHAM reveal that wind shear is as important as other processes like the treatment of precipitation in the updraft and mid-level convection. Overall, the scheme with all physical processes included tends to perform best in single column as well as in AMIP simulations.
Hohenegger, Cathy

Max Planck Institute for Meteorology
cathy.hohenegger@mpimet.mpg.de

Coupled radiative convective equilibrium simulations with explicit and parameterized convection

Cathy Hohenegger and Bjorn Stevens

Radiative convective equilibrium (RCE) has been used as a simplified analog for the tropical climate. Here the equilibrium state reached by two simulations using different representations of convection is compared and differences investigated. The first simulation uses convection-permitting resolution (3 km grid spacing) and thus an explicit representation of convection. In the second simulation, due to its coarse resolution (T63), convection is parameterized. Both simulations are coupled to an ocean mixed layer model and integrated with a diurnally varying insolation until the surface energy budget reaches equilibrium. Analysis of the two simulations reveals the existence of multiple equilibrium states: a very warm and moist state, a warm and dry state and a cloudy and cold state. The first two states are possible solutions of the convection-permitting simulation. The initial imbalance in surface energy is compensated either by a strong surface warming and enhancement of the latent heat flux or by a reduction of the downward longwave radiation. This second possibility occurs if convection self-aggregates. In contrast the low-resolution simulation with parameterized convection closes its surface energy budget through the production of numerous clouds. In this case the cloud cover amounts to 0.5 versus 0.2 in the convection-permitting simulation. Reasons for such differences are investigated.
Holloway, Chris

University of Reading
c.e.holloway@reading.ac.uk

Convective aggregation mechanisms: from idealised to realistic convective organization

Idealised explicit convection simulations of the Met Office Unified Model are shown to exhibit spontaneous self-aggregation in radiative-convective equilibrium, as seen previously in other models in several recent studies. This self-aggregation is linked to feedbacks between radiation, surface fluxes, and convection, and the organization is intimately related to the evolution of the column water vapour (CWV) field. To investigate the relevance of this behaviour to the real world, these idealized simulations are compared with five 15-day cases of real organized convection in the tropics, including multiple simulations of each case testing sensitivities of the convective organization and mean states to interactive radiation, interactive surface fluxes, and evaporation of rain. Despite similar large-scale forcing via lateral boundary conditions, systematic differences in mean CWV, CWV distribution shape, and the length scale of CWV features are found between the different sensitivity runs, showing that there are at least some similarities in sensitivities to these feedbacks in both idealized and realistic simulations. Estimates of the rate at which interactive radiation affects these differences in realistic cases are made.
Hoose, Corinna

Karlsruhe Institute of Technology

corinna.hoose@kit.edu

Comparing model and satellite views of the liquid/ice partitioning in developing convective clouds

The transition from liquid water to ice in the atmosphere can occur either via homogeneous freezing at temperatures of approximately -37°C, or with the help of an aerosol particle or an ice crystal as ice nucleating particle. Once the first crystals have formed, they can grow on the expense of evaporating droplets and/or induce ice multiplication processes, both leading rapidly to a full glaciation of the cloud. In-situ data show that the phase transition typically occurs around -15°C, but these observations are based on a very limited dataset and mostly refer to stratiform clouds with moderate liquid water contents. In recent years, advanced retrieval schemes for the liquid and ice occurrence at cloud top have been developed for passive satellite sensors, offering global coverage (e.g. MODIS, AVHRR) and regional coverage at high temporal (e.g. SEVIRI) both at decent spatial resolution of 1 to 5 km.. These data can be used to study regime dependencies, trends and aerosol impacts on the cloud phase distribution. However, it is uncertain how these observations of cloud-top quantities relate to the phase distribution within the clouds. To investigate this question, we have used semi-idealized simulations with a horizontal resolution of 110 m to study the liquid/ice partitioning within the cloud and at cloud top for an evolving deep convective cloud. In general, we find that the in-cloud and cloud-top phase distributions are qualitatively similar and exhibit similar sensitivities to microphysical processes. However, we show that at a given temperature, the simulated average ice mass fraction is higher at cloud top than within the cloud. This is due to the suppression of the Wegener-Bergeron-Findeisen process in strong updrafts. Furthermore, we investigate the sensitivity of the diagnosed glaciation temperature to the resolution and to the minimum optical depth required for the definition of cloud top.
Imamovic, Adel

ETH Zurich
adel.imamovic@env.ethz.ch

Combined impacts of soil moisture and topography on summertime convection initiation in idealized simulations

The prediction of the initiation of summertime moist convection has remained a major bottleneck for quantitative precipitation forecasting. The triggered thunderstorms are often abrupt, accompanied by damaging winds or heavy rain and thus of great socio-economic importance. These short-scale events are not only an essential challenge for numerical weather prediction (NWP): the representation of the mechanisms driving convection initiation in regional climate models also strongly determines where precipitation preferentially occurs in present and future summer climate. Computational advances in the past years pushed the resolution limits towards the convective scale $O(1 \text{ km}, 100 \text{ m})$. This new realm liberated NWP and regional climate models from the utilization of convection parametrization schemes. Recent regional climatologies based on convection-resolving models show some major improvements over convection-parametrizing models, such as a better representation of hourly precipitation statistics and the diurnal cycle. In combination with a better representation of the soil-moisture distribution and the complexity of terrain, the higher resolution also allows for a more adequate representation of mesoscale circulations. Their role in the hydrological cycle is important, as they are known to strongly control the time and location of convection initiation, especially under weak synoptic conditions. We present results from an idealized study using the convection-resolving Consortium for Small-Scale Modeling (COSMO) model at 1 km horizontal resolution. We investigate the combined impacts of soil-moisture anomalies and topography on timing, location and strength of summertime convection initiation under weak synoptic forcing. Furthermore we document (1) how the dynamical coupling between the mesoscale circulations and the large-scale background amplifies or dampens the convection initiation and (2) how different turbulence formulations affect the processes involved.
Jakob, Christian

Monash University

christian.jakob@monash.edu

A new framework for cumulus parametrisation - Ideas, observations and first results

The basic principle underpinning the parametrisation of tropical convection in global weather and climate models is that there exist discernible interactions between the resolved model scale and the parametrised cumulus scale. Furthermore, there must be at least some predictive power in the larger scales for the statistical behaviour on small scales for us to be able to formally close the parametrised equations. The presentation will discuss a new framework for cumulus parametrisation based on the idea of separating the prediction of cloud area from that of velocity. This idea is put into practice by combining an existing multi-scale stochastic cloud model with observations to arrive at the prediction of the area fraction for deep precipitating convection. Using mid-tropospheric humidity and vertical motion as predictors, the model is shown to reproduce the observed behaviour of both mean and variability of deep convective area fraction well. Extensions to the framework, such as the inclusion of other types of convection, convective organisation, as well as resolution-awareness will be discussed. When combined with simple assumptions about cloud-base vertical motion the model can be used as a closure assumption in any existing cumulus parametrisation. Early results of applying this idea in the the ECHAM model indicate significant improvements in the simulation of tropical variability, including but not limited to the MJO.
Jakub, Fabian

Meteorological Institute Munich

fabian.jakub@physik.uni-muenchen.de

Three Dimensional Radiative and Convective Equilibrium

We present a novel method to calculate three dimensional heating rates in cloud resolving models. The TenStream algorithm is a generalization of the well known one dimensional two-stream formalism to ten streams in three dimensions. Earlier studies showed that the effects of three dimensional radiative transfer may impact cloud formation and precipitation. The major effects, neglected by one dimensional solvers, are cloud side illumination and the displaced cloud shadow at the surface. For the first time, the TenStream solver allows to simulate unprecedented large domains for extended periods of time. The TenStream model was coupled to the HDCP^2 benchmark model, UCLA-LES. We will discuss the impact that three dimensional radiative transfer has on cloud evolution and convective organization in radiative convective equilibrium.
Atmospheric chemistry effects on cloud - representing aqueous phase chemical reactions in a particle-based cloud-microphysics scheme.

Aerosol particles provide nuclei on which cloud droplets form (cloud condensation nuclei - CCN). If a cloud develop precipitation some of the CNN are removed from the atmosphere. However, due to evaporation of cloud droplets and drizzle drops, part of the CCN remains in the atmosphere. Remaining CCN have altered physiochemical properties if the evaporated droplets went through collisional growth or irreversible chemical reactions (e.g. SO2 oxidation). Hence, the aerosol particles influence cloud microphysical properties, and in turn, cloud microphysical and chemical processes may affect aerosol size spectrum and its chemical composition. The main challenge of representing these processes in a numerical cloud model stems from the need to track the properties of activated CCN and the chemical composition of cloud droplets throughout the cloud lifecycle. Tracking particle properties is an inherent feature of the particle-based frameworks. In this study we apply the particle-based scheme of Shima et al. 2009. Modeled particles (aka super-droplets) are a numerical proxy for a multiplicity of real-world CCN, cloud, drizzle or rain particles of the same size and chemical composition. The super-droplet approach features particle-level formulation of condensational (including CCN activation and evaporation) and collisional growth of cloud droplets. This study will focus on presenting the newly implemented aqueous chemistry module featuring a particle-level representation of aqueous phase SO2 oxidation by H2O2 and O3. The presented scheme will be used in a 0D-parcel and 2D-kinematic framework. The former will allow to test the implementation of the new chemistry module. The latter will mimic a vertical slice of a stratocumulus cloud, and allow to showcase the preliminary results of simulations with both collisions and chemical reactions present. The described super-droplet scheme and its aqueous phase chemistry extension is packaged as an open-source software library, ready to download and use on either GPU or CPU. Although the library itself was implemented in C++ it was successfully used from models written in Python and FORTRAN. Both the source-code and the documentation are available at http://libcloudphxx.igf.fuw.edu.pl/.
Jensen, Michael

Brookhaven National Laboratory

mjensen@bnl.gov

An Observational Study of Environmental Factors Limiting Tropical Convective Cloud Growth

We use observations from the ARM Climate Research Facility sites in the tropical Western Pacific and tropical AMF deployments to revisit the growth of cumulus congestus clouds and the factors that control their lifecycle (Jensen et al. 2006). We revisit the relative importance of freezing layer stability and mid-tropospheric dry layers in limiting the growth of terminal cumulus congestus considering only “terminal” congestus clouds (Luo et al. 2009). We use radar-observed Doppler velocities to determine the state (“terminal” vs. “transient”) of cloud growth. We then investigate how cloud parcel buoyancy and bulk entrainment of individual clouds are impacted by environmental conditions. Preliminary results for analysis of the full observational record at Nauru support the original conclusions from Jensen et al. (2006) that bulk entrainment rate decreases as a function of congestus cloud-top height and the mid-level humidity is the critical factor limiting tropical congestus cloud growth.
Jousse, Alexandre

UCLA
joussea@g.ucla.edu

Low Cloud Cover Anthropogenic Changes in the California Region

In this study, we analyze the low cloud cover response to anthropogenic climate signals in the California region. Five general circulation models representing the full range of CMIP5 projections in sea surface temperature and inversion strength are dynamically downscaled with the Weather Research and Forecasting (WRF) model. WRF future simulations exhibit a systematic decrease in low cloud cover. To evaluate the reasons to these results, we develop a methodology of analysis that quantifies the factors contributing to low cloud cover changes. Our study shows that WRF anthropogenic decrease in low cloud cover is mostly imputable to a reduction of the coupling between boundary layer top and surface. Our analysis suggests that these changes are likely driven by the relative drying of the free troposphere in comparison to the boundary layer in future climate. We also investigate the possible use of observations to constrain WRF simulated results.
Exploiting cloud radar Doppler spectra of mixed-phase clouds to identify microphysical processes

Cloud radar Doppler spectra offer much information about cloud processes. By analyzing millimeter radar Doppler spectra from cloud-top to base in mixed-phase clouds in which super-cooled liquid-layers are present we try to tell the microphysical evolution story of particles by disentangling contributions of solid and liquid particles to the total radar returns. Instead of considering vertical profiles, dynamical effects are taken into account by following the particle population evolution along slanted paths caused by horizontal advection of the cloud. The goal is to identify regions in which different microphysical processes such as new particle formation (nucleation), water vapor deposition, aggregation, riming, or sublimation dominate. Cloud radar measurements are supplemented by Doppler- and Raman lidar as well as microwave radiometer and radio sondes. The vertical location of liquid layers (in non-raining systems and below lidar extinction) is derived from regions of high-backscatter and low depolarization in Raman lidar observations. In collocated cloud radar measurements, we try to identify cloud phase in the cloud radar Doppler spectrum via location of the Doppler peak(s), the existence of multi-modalities or the spectral skewness. Additionally, within the super-cooled liquid layers, the radar-identified liquid droplets are used as air motion tracer to correct the radar Doppler spectrum for vertical air motion $w$. These radar-derived estimates of $w$ are validated by independent estimates from collocated Doppler lidar measurements. The methodology is illustrated using data from the deployment of the Leipzig Aerosol and Cloud Remote Observations System (LACROS) during the Analysis of the Composition of Clouds with Extended Polarization Techniques (ACCEPT) field experiment in Cabauw, Netherlands in Fall 2014 as well as using data from the deployment of the Atmospheric Radiation Measurement Program’s (ARM) mobile facility AMF2 at Hyytiälä, Finland during the BAECC (Biogenic Aerosols – Effects on Clouds and Climate Snowfall Experiment) field experiment in 2014.
Kaul, Colleen

ETH Zurich

ckaul@ethz.ch

Simulations of stably-stratified boundary layers using a novel large eddy simulation infrastructure

Stable boundary layers occur ubiquitously in the Arctic region under both clear-sky and cloudy conditions and must be accurately represented for models of Arctic climate to be reliable. While large eddy simulations (LES) can provide insight into the structure and evolution of stable boundary layers, this is a notoriously difficult area of application for LES techniques due to the suppressed and sometimes intermittent nature of turbulence under conditions of stable stratification. This work reports on simulations of clear and cloud-topped stable boundary layers based, respectively, on the GABLS (Beare et al., 2006) and ISDAC (Ovchinnikov et al., 2014) cases, using the recently developed large eddy simulation infrastructure known as PyCLES (Pressel et al., 2015). The analysis particularly focuses on the effects of the high-accuracy, non-oscillatory, and non-dissipative numerical schemes that are a distinctive feature of the PyCLES implementation and their potential to alleviate the typical stringent grid resolution requirements on LES of stable boundary layers.
Kern, Bastian

DLR

bastian.kern@dlr.de

Applying on-line diagnostic tools in high resolution modelling

Input and output (I/O) of simulation data is an important aspect in high performance computing (HPC). Especially in high resolution numerical simulations over large domains with a high degree of distributed memory parallelisation I/O becomes a limiting factor. In the last years computational throughput of HPC systems increased, opening the ability to operate numerical weather and climate models with increasingly finer resolutions. This results in increasing amounts of data output from the model system. From the user's perspective the problems arise, where to store and archive these data, and which tools to use for subsequent post-processing. Transferring large data between different systems and subsequent processing require additional I/O operations, repeatedly hitting the I/O bottleneck and also memory limits of the computing system, if postprocessing is performed serially. One way to deal with I/O limitations is reducing the amount of output data by coarse-graining, although this may abandon advantages previously gained through the finer resolved simulations in subsequent processing. In contrast, on-line diagnostic tools use the fully resolved data, perform data reduction, and enable advanced diagnostics, which are not applicable off-line. We introduce a general and standardised interface to include sophisticated on-line diagnostic tools into the ICOsahedral Non-hydrostatic (ICON) modelling framework based on the Modular Earth Submodel System (MESSy). We present results of a novel complex on-line diagnostic tool calculating joint-PDFs on a coarse regular grid from high-resolution simulations. This also includes runtime analyses to evaluate additional computational costs from the on-line diagnostic and from the diagnostic interface itself. Furthermore, we give an overview of diagnostic tools, which were implemented or are currently under development using the diagnostic interface. We also present an outlook of future projects with enhanced on-line diagnostics. The presented work helps to overcome some of the limitations, which occur when going to even higher resolutions. The standardised interface and the on-line diagnostics will provide helpful and sophisticated tools for process oriented analyses of high resolution simulations, and will help to reduce the user’s burden of handling large data from high resolution simulations.
Khairoutdinov, Marat

Stony Brook University

marat.khairoutdinov@stonybrook.edu

**Near-Global Simulations of Aquaplanet with CRM**

The idealized near-global aquaplanet cloud-resolving simulations produced by the System for Atmospheric Modeling (SAM) CRM over prescribed SST patterns are analyzed. The computation domain has been similar to the Earth's equatorial circumference and extended up to the extra tropics in the north and south limited by rigid walls. The radiation is interactive with diurnal cycle. The horizontal grid spacing is 4 km. The SST patterns have been based on the standard Aqua-Planet Experiment (APE) SSTs. The results of the +4K and 4xCO2 perturbation experiments will be presented.
Kinne, Stefan

Max Planck Institute for Meteorology

stefan.kinne@mpimet.mpg.de

Aerosol direct and indirect climate effects

The MACv2 aerosol climatology for aerosol optical properties is applied to determine the aerosol impact on climate. While direct effects are simply a radiative transfer application, estimates are more complicated for aerosol indirect effects. Most prominently, aerosol offers added cloud nuclei, which can increase the cloud droplet concentrations (CDNC) to increase the (low) cloud albedo. The relevant aerosol properties are (1) extra aerosol concentrations at cloud based, (2) already existing aerosol concentrations at cloud-base, (3) aerosol composition, (4) temperature and (5) supersaturation. Based on the optical data of the MACv2 climatology needed aerosol (microphysical) properties at cloud base are derived and associated estimates for aerosol indirect effects are determined. Particular interesting is the spatial distribution of these aerosol indirect effects and how this pattern differs from those derived from much simpler relationships that (e.g. joint histograms for satellite retrievals of fine-mode aerosol optical depth (AODf, as proxy for aerosol number concentration) and co-located CDNC estimates.
Kipling, Zak

University of Oxford

zak.kipling@physics.ox.ac.uk

Using convection-permitting simulations to constrain the parameterised cloud spectrum at the sub-grid scale

Most general circulation models (GCMs) used for global climate simulations use bulk mass-flux convection parameterisations, which approximate the ensemble of convective clouds within each GCM column by a single “mean” convective updraught. This neglects the marked spatial inhomogeneity of convective cloud in many regimes on the model grid scale and the consequent nonlinear effects. The Convective Cloud Field Model (CCFM) overcomes this limitation, representing a spectrum of different convective updraughts within each grid column. Each is represented by a Lagrangian entraining plume with explicit cloud microphysics, with the spectrum itself determined dynamically by competitive interactions via the large-scale environment. Embedded in the global climate model ECHAM–HAM, CCFM represents global cloud and precipitation distributions well as compared to the Tiedtke–Nordeng mass-flux scheme normally used. Beyond this, CCFM can provide diagnostic information on the sub-grid-scale cloud morphology which is not available from a mass-flux parameterisation. This opens the way for new evaluation techniques based on statistical comparison against high-resolution simulations at the cloud and cloud-system scale. In this study, we evaluate the sub-grid-scale cloud-top height distributions from CCFM using a convection-permitting WRF simulation with a 1km grid spacing over the Congo basin. We show how this can help to validate the physical basis of the parameterisation closer to the process level than considering only the effects of convection on the resolved scale. We then adapt this technique to derive constraints on the uncertain parameters in the convection scheme that are based on the behaviour of convective cloud itself rather than tuning for large-scale climate variables. By looking at the differences which remain, we identify aspects of the parameterisation which would likely benefit from further refinement.
Emergent constraints for the climate prediction of clouds and precipitation

Emergent constraints are physically-explainable empirical relationships between characteristics of the current climate and long-term climate prediction that emerge in collections of climate model simulations. When combined with an observational estimate of the current climate characteristics, they seemingly offer the prospect of constraining long-term climate prediction. In this talk, I will review three constraints discovered by researchers in the LLNL–UCLA Cloud Feedbacks project involving tropical and extra-tropical low-level clouds and global mean precipitation. Because emergent constraints identify a source of model error that projects onto climate predictions, they deserve extra attention from those developing climate models and climate observations. While a systematic bias cannot be ruled out, the emergent constraints I review suggest larger cloud feedbacks and smaller precipitation sensitivity. This work is performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE–AC52–07NA27344.
Impact of 3D thermal radiation on the development of clouds

Solar and thermal radiation drive weather and climate and strongly affect cloud formation. In the solar spectral range, radiation passes the atmosphere and heats the ground. The generated updrafts transport moist air which condenses while rising and eventually forms clouds and precipitation. In the very moment a cloud forms, this updraft can be weakened by the reduction of the irradiance at the ground due to the shadow of the cloud or neighboring clouds. Similarly, absorption and emission of radiation occur in the atmosphere which is usually described by heating and cooling rates. The typical radiative impact under cloudless conditions is a cooling of -1 to -2 K/d. However, heating or cooling rates can become orders of magnitude larger (several 100 K/d) at the interface between clouds and atmosphere which directly feed back onto the cloud in terms of a warming at the illuminated cloud side in the solar and strong cooling at the cloud top and cloud sides as well as modest warming at the cloud bottom in the thermal spectral range. Accurate radiative transfer models exist to calculate 3D heating and cooling rates. These are usually based on the Monte Carlo method and are computationally too expensive to be used to calculate diabatic heating in cloud resolving models. Due to the complexity and the computational costs of accurate 3D radiative transport, radiation is therefore often neglected completely in today’s cloud resolving models or at best treated using a plane-parallel 1D approximation which neglects horizontal radiation transport. This approximation causes considerable uncertainty (e.g. the neglect of cloud side cooling). Due to the fact that 3D radiative transfer is rather expensive, the impact of 3D thermal radiation on clouds has never been investigated in detail before. We present a fast method to calculate 3D thermal radiative transfer in cloud resolving models, which allows for the first time to study these 3D effects. The parameterization can be considered a post-processing of the results of a regular 1D solver and takes advantage of the effect that in first approximation we only need the information if a pixel is at the edge of a cloud or not. The neighbouring column approximation (NCA) therefore only needs to access the neighbouring columns which results in a method that can be efficiently parallelized. The NCA has been implemented into the UCLA-LES to study the impact of 3D thermal radiation on clouds. The NCA and application studies showing the impact of 3D radiation on clouds will be presented.
Mechanisms of small scale error growth in high-resolution simulations

Parametrized physical processes do not represent variability on small scales and hence cannot describe the error growth originating from small scales. Especially moist processes like convection and cloud formation have strong impact on error growth rates. We focus on the first hours of a shallow convective day in high resolution model data to analyze the growth rates and growth mechanisms of small initial perturbations during the development of the boundary layer.
Kneifel, Stefan

*University of Cologne*

skneifel@meteo.uni-koeln.de

**Triple-frequency cloud radar approach: A novel way to investigate aggregation and riming processes in clouds**

Recent theoretical and observational studies indicated that triple-frequency radar measurements (e.g. combining 10, 35, and 95 GHz) bear the potential to derive important snow and ice microphysical parameters like median mass diameter, fractal dimension, or particle habit. However, direct comparisons with in-situ observations to validate these predictions were still missing. In this presentation we will show results from a recent field campaign in Finland where ground-based triple-frequency radar observations are for the first time analyzed in combination with a comprehensive set of collocated in-situ observations. The comparisons revealed a close link between the unique signatures in the triple-frequency space to key hydrometeor properties like particle density and characteristic size of the particle size distribution – quantities which cannot be disentangled with conventional single-frequency cloud radars. We will also present recent analysis of the full triple-frequency Doppler spectra and demonstrate how their information can be used to validate ice and snow particle scattering models and to constrain velocity-size relations of the underlying particle population. Finally, initial results of analyzing triple-frequency observations together with the polarimetric fingerprints of two nearby scanning polarimetric radars will be shown. These observations have been obtained during the first German triple-frequency experiment at the Research Centre Jülich (FZJ) during 2015 which was a collaborative effort of the U. Cologne, U. Bonn, FZJ and Karlsruhe Institute of Technology (KIT) to further explore the potential of combining triple-frequency, Doppler spectra, and polarimetric radar techniques to obtain detailed observational information about complex ice microphysical processes.
Knippertz, Peter
Karlsruhe Institute of Technology
peter.knippertz@kit.edu

The challenge of modeling low-level cloudiness in the West African monsoon region

The southern parts of West Africa are frequently covered by an extensive deck of shallow, low (200–400 m above ground) stratus or stratocumulus clouds during the summer monsoon season. Climatologically, the ultra-low stratus decks form after sunset along the Guinea coast, spread inland and reach about 10-11°N between 0900 and 1000 UTC of the following day. In the late morning the northern boundary gets fragmented due to the breakup of stratus decks into fair-weather cumuli. A thorough validation of weather and climate models with respect to this process is challenging due to a lack of local observations and a misrepresentation of ultra-low cloud decks in most satellite products. Nevertheless it could be shown that Coupled Model Intercomparison Project 3 (CMIP3) global climate models largely failed to represent these clouds, leading to errors in surface solar radiation of up to 90 W m−2. New results using CMIP5 and YOTC (Years of Tropical Convection) GASS (GEWEX Atmosphere System Study) global climate models show that the representation of low-level cloudiness has not improved in the latest generation of global models. Large systematic errors are even found in much higher-resolution model simulations, e.g. using the COSMO model. Recent high-resolution simulations using the WRF model in contrast have shown promising results after a careful selection of boundary layer and surface schemes. They reveal that the night-time cloud formation is related to a subtle balance between “stratogenic” upward (downward) fluxes of latent (sensible) heat caused by shear-driven turbulence below the night-time low-level jet, cold advection, orographic lifting and radiative cooling on one hand, and “stratolytic” dry advection and latent heating on the other hand. Results from these and other new simulations are currently being used to better understand deficits in other models and to explore impacts on the larger-scale monsoon circulation and precipitation.
Kodama, Chihiro

JAMSTEC/MPI-M

kodamac@jamstec.go.jp

A 20-year climatology simulated by non-hydrostatic icosahedral atmospheric model NICAM

A 20-year integration by Non-hydrostatic Icosahedral Atmospheric Model (NICAM) with a 14-km mesh was conducted for the first time to obtain a climatological mean and diurnal-to-interannual variability of a simulated atmosphere. Clouds were explicitly calculated using a cloud microphysics scheme without cumulus convection scheme. The simulation was performed under the Atmospheric Model Intercomparison Project (AMIP)-type conditions except that sea surface temperature was nudged toward observed historical values using a slab-ocean model. The results are analyzed with a special focus on tropical disturbances, including tropical cyclones (TCs) and the Madden-Julian oscillation (MJO). NICAM reasonably simulates many aspects of atmospheric climatological mean state and variability. Geographical distributions of precipitation, including interannual, seasonal and diurnal variations are well reproduced. In addition, zonal mean basic states, clouds and top-of-atmosphere radiation are comparable to observed values. TCs and MJO are the major focus of the simulation. In the simulation, TCs are detected with objective thresholds of maximum wind speed, owing to the realistic intensity of simulated TCs. Seasonal march of TC genesis in each ocean basin is well simulated. Statistical property of the MJO and tropical waves is well reproduced in the space-time power spectra, consistent with previous NICAM studies. This implies that the stratospheric variability is also reproduced, as partly revealed in this study. Asian monsoon analysis shows that climatological western North Pacific monsoon onset occurs near the observed onset, and that the Baiu front is reproduced to some extent. Some significant model biases still exist, which indicates a need for further model improvements. The results of this study indicate that a high-resolution global non-hydrostatic model has the potential to reveal multi-scale phenomena in the climate system.
Kollias, Pavlos

Stony Brook University

pavlos.kollias@mcgill.ca

Advancing Cloud and Precipitation Research at the new ARM radar facilities

The challenge of reducing uncertainties in future climate predictions coupled with the growing pressure to accelerate progress in cloud parameterization calls for a rethinking of efforts to observe atmospheric processes. Part of the problem lies with past constraints that limited our observing capabilities to only parts of the systems and the process chain. The ARM program strives to overcome this limitation by operating new radar facilities capable of providing holistic multi-scale observations of clouds and precipitation to better understand the water and energy cycles in our climate system. The new ARM program radar installations include radars that operate at five frequency bands covering a wide range of scattering mechanisms, thus improving the information from collocated multi-wavelength observations. This is particularly true in the vertical column, thus, providing enhanced, calibrated, multi-parametric measurements of clouds and precipitation. In addition, the ARM program radar network features scanning polarimetric Doppler radar observations and exploits polarimetry to provide a wealth of information about storm system microphysics and dynamics under a wide range of climatological conditions. The main objectives of these ARM program radar upgrades are to provide a revolutionary characterization of volumes of the cloudy atmosphere over long periods of time and to act as a natural laboratory for the modeling community both for testing models (model evaluation) and for improving parameterizations of clouds. The configurable ARM program radar network will employ adaptive scanning strategies that enable focused experiments to study critical aspects of the water and energy cycles at a range of spatial scales from the inner scale (30-50 m) to the outer scale (50-100 km).
Konow, Heike

University of Hamburg

heike.konow@uni-hamburg.de

NARVAL-North: Cloud Properties from Aircraft Measurements and Model Evaluation

Representation of cloud and precipitation processes is one of the largest sources of uncertainty in climate and weather predictions. To validate model predictions of convective processes over the Atlantic ocean, often satellite data are used. However, satellite products provide just a coarse view with poor temporal resolution of convection over the Atlantic. The new research aircraft HALO (High Altitude Long Range Research Aircraft) provides the unique opportunity to exploit regions of the atmosphere that can not be easily accessed otherwise as it is able to reach remote regions and operate from higher altitudes than other aircraft. These measurements give more detailed insights than satellite data can provide. Therefore, this measurements platform bridges the gap between previous airborne measurements and satellites. The NARVAL-North (Next-generation Aircraft Remote-Sensing for Validation Studies) campaign was conducted in January 2014 out of Keflavik (Iceland) to investigate cloud and precipitation properties in post-frontal mesoscale convective systems at high latitudes above the Atlantic ocean. It was one of the first campaigns that took place on HALO. During the experiment, five research flights and two transfer flights were conducted. A broad range of cloud regimes from shallow cumuli to cumulonimbus and cold fronts was investigated. HALO was, amongst others, equipped with the HALO Microwave Package (HAMP) which consists a suite of passive microwave radiometers at a range of frequencies and a cloud radar at 36 GHz. Measurements taken during the NARVAL campaign will be presented. These will help to evaluate cloud properties derived from COSMO simulations. We will demonstrate new insights from this novel type of observations. Model biases, the representation of cloud structures compared with observations, performance of forward operator and the relation to ambient air conditions will be analyzed. This comparison study enables to identify possibilities for improvement of modeling clouds and precipitation of weather systems over oceans at higher latitudes.
Krueger, Steve

University of Utah

steve.krueger@utah.edu

Merging Cumulus Updrafts

The updrafts that produce deep cumulus clouds have long been conceptually viewed and parameterized as only interacting indirectly, through their collective effects on the large-scale fields. However, it is well-known (and simulated by cloud-resolving models) that cumulus updrafts and downdrafts do indeed directly interact, thereby allowing convection to organize. One aspect of such direct interaction that has received little attention is updraft merging. When updrafts develop in close proximity it is possible for them to merge, and thereby produce a larger and less rapidly entraining updraft compared to its precursors. Updraft merging at some height above cloud base level may be able to explain several puzzling features of near-cloud-base updraft properties. Updraft merging is favored by situations that congregate updrafts, such as gust fronts produced by convective cold pools. We are analyzing large-eddy simulations of deep convection to determine the importance of updraft merging and the factors that favor its occurrence. We are also considering how to incorporate the effects of updraft merging into cumulus parameterizations.
Kuhn, Alexander

Zuse-Institute Berlin (ZIB)

kuhn@zib.de

Feature-based Analysis of Clouds and Precipitation Systems in Meteorological Data

Clouds and precipitation systems are fundamental features in the global climate cycle and are one focus aspect of recent high resolution, cloud resolving simulation and measurement modalities. Such highly resolution data sources allow for more precise methodologies to extract and track such features and enable novel evaluation tasks such as life-cycle tracking, feature-based statistics, and feature-based comparison of simulation and measurements. However, their complex dynamics and highly variable shape morphology makes extraction and tracking of clouds and rain objects challenging tasks with respect to stable and reliable processing algorithms. We will present our efforts on establishing an community-wide inter-comparison study to provide an overview of state-of-the-art algorithms for cloud extraction and tracking. We propose a set of 2D and 3D benchmark data sets (from simulations and measurements) that are used as a common basis for comparison. In addition we describe a web-based feature-based evaluation framework and provide an in depth analysis and comparison of those algorithms. The goal of our work is to systematically compare and assess numerical extraction and tracking techniques for cloud features in meteorological data and provide a comprehensive overview of suitable application scenarios, describe current strengths and limitations, and derive statements about their variability for feature-based analysis tasks. In addition, we will discuss, evaluate and compare novel approaches for tracking of such meteorological features.
New development in convection and convective microphysics parametrisations: Results and implications for climate modeling.

One of the challenges for convective parameterisations is to represent the impact of convective clouds at the scale of a typical Global Climate Model gridbox (~100 km). Most GCMs represent convection by a single average mass-flux. This is computationally efficient but insufficient to represent the sub-grid scale variability of convective cloud properties (size, microphysics, precipitation rate, ...). To overcome this issue we use the Convective Cloud Field Model (CCFM) in the aerosol-climate model ECHAM-HAM, and compare it with the default Tiedtke-Nordeng scheme. CCFM simulates a spectrum of clouds with different radii, vertical extents and updraft velocities, while the Tiedtke-Nordeng scheme uses a bulk mass-flux approach. With the Tiedtke-Nordeng scheme, the temporal autocorrelation of precipitation decreases very quickly, indicating a very high intermittency of the precipitation, while CCFM results are much closer to the observations, with a high autocorrelation of the precipitation over short time scales. CCFM provides various updraft velocities (within one gridbox) allowing the representation of clouds with various microphysical properties and responses to aerosol content. In order to take full advantage of CCFM for representing aerosol-cloud interactions and studying the convective microphysics, we implemented the Predicted Particle Properties microphysics scheme (P3, Morrison and Milbrandt, 2015, JAS), a state of the art two-moment scheme with free ice categories initially developed for WRF. We also investigate the impact of the new microphysics on the characteristics of convection and its response to changes in aerosol concentration to finally present the microphysical pathways, and their links with the large-scale variables. The results from single column simulations are compared with WRF simulations and observations. This gives us guidelines to determine the degree of complexity required to represent convective microphysics and aerosol-convection interactions in a GCM.
Lammert, Andrea

*University of Hamburg*

[andrea.lammert@uni-hamburg.de](mailto:andrea.lammert@uni-hamburg.de)

**A new culture of storing observational data in Atmospheric Research**

A new culture of storing observational data in Atmospheric Research Andrea Lammert and Erasmia Stamnas Within the project HD(CP)$^2$ we have developed and established a new data archive for atmospheric observations. In phase 1 we have defined consistent standards for atmospheric measurement data, comparable to and, where possible, adopting the Climate Forecast (CF) conventions. This step ensures an easy usability of the data, e.g. for model evaluation. The observation standard includes the huge variability of atmospheric observations, as instruments, quantities, temporal and spatial resolution, long term and campaign data. The fantastic HDCP$^2$ observation community has put a lot of time and efforts into reformatting and processing the measurement data according to this standard and to provide the data to our data base. This data base is a new development, based on THREDDS technology (distributed Server in Cologne, Berlin, and Leipzig). The data are available via the HDCP$^2$ web portal, which provides extensive and consistent meta data for each data set. With all these steps we have established a new culture for storing atmospheric observation data in a standardized format, which is highly compatible with the CF standard. The main goals for the future are the transfer of the existing archive in a sustainable structure and the opening of the archive to the whole research community. Therefore we have to develop a user registration tool and a user administration. Additional we will develop a prototype data server to enable researchers to include their own server into our network and provide their data via our web portal.
Langhans, Wolfgang

Lawrence Berkeley National Laboratory

wlanghans@lbl.gov

The origin of water vapor rings in tropical oceanic cold pools

Tropical deep convection over the ocean is found to grow preferentially from thermodynamically pre-conditioned regions of high specific humidity and, thus, high moist static energy. For this reason, rings of enhanced specific humidity at the leading edges of evaporatively driven cold pools have recently received considerable attention. The prevailing theory explains these rings by the water-vapor source from the evaporation of rain drops below cloud base. Their origin is studied in this letter using large-eddy simulations of individual cumulus clouds that rise into a tropical atmosphere over ocean. It is demonstrated that -- in contrast to this theory -- water-vapor rings are primarily explained by surface latent-heat fluxes rather than by the evaporation of rain. This finding implies that conceptual models used in subgrid-scale parameterizations of deep convection should consider the formation of rings of increased specific humidity by the cold-pool-induced enhancement of surface fluxes.
L'Ecuyer, Tristan

University of Wisconsin

tristan@aos.wisc.edu

Toward Linking Cloud Properties and Precipitation using A-TRAIN Observations

After nearly a decade of formation flying, the active and passive sensors in the A-Train constellation have provided valuable insights into relationships between clouds, precipitation, and their environment. This presentation will review the physical considerations behind the unique precipitation detection capabilities afforded by space-based millimeter-wavelength cloud radar measurements and summarize recent advances in converting these measurements to global precipitation datasets. New methodologies for identifying convective cores at high spatial resolution and retrieving profiles of light rain and falling snow will be discussed. Recent applications of these products to understand the spatial characteristics of precipitation and their relationship to associated cloud cover will be highlighted.
Geert Lenderink, Pier Siebesma and Jessica Loriaux, KNMI

A dependency of (sub)hourly precipitation extremes on the dew point temperature close to 12-14% per degree has been found in a number of studies. This dependency is twice as large as the dependency following surface humidity, which is directly given by the Clausius-Clapeyron relation (i.e. 6-7% per degree). It is often argued that changes in precipitation extremes in a warming climate should follow a CC scaling, and the factor 2 enhancement in the observations is therefore noteworthy. There is a large debate on the generality and causality of this 2-CC relation. Our hypothesis is that it is due to dynamical feedbacks from convective cloud dynamics due to latent heat release. In support of this statement we will present results from a simple conceptual model consisting of an entraining plume, which represent the cloud core. Also results with a mesoscale model are presented. If, as we believe, 2-CC scaling is a property of convective precipitation, then it may also provide a useful constraint on future changes.
Leutwyler, David

ETH Zurich
david.leutwyler@env.ethz.ch

A Decade-long Continental-Scale Convection-Resolving Climate Simulation on GPUs


The representation of moist convection in climate models represents a major challenge, due to the small scales involved. Convection-resolving models have proven to be very useful tools in numerical weather prediction and in climate research. Using horizontal grid spacings of $O(1\text{km})$, they allow to explicitly resolve deep convection leading to an improved representation of the water cycle. However, due to their extremely demanding computational requirements, they have so far been limited to short simulations and/or small computational domains. Innovations in the supercomputing domain have led to new supercomputer-designs that involve conventional multicore CPUs and accelerators such as graphics processing units (GPUs). One of the first atmospheric models that has been fully ported to GPUs is the Consortium for Small-Scale Modeling weather and climate model COSMO. This new version allows us to expand the size of the simulation domain to areas spanning continents and the time period up to one decade. We present results from a decade-long, convection-resolving climate simulation using the GPU-enabled COSMO version. The simulation is driven by the ERA-interim reanalysis. The results illustrate how the approach allows for the representation of interactions between synoptic-scale and meso-scale atmospheric circulations at scales ranging from 1000 to 10 km. We discuss the performance of the convection-resolving modeling approach on the European scale. Specifically we focus on the organization of convective clouds such as the initiation of new convective cells by propagating cold pools and on the statistics of hourly rainfall.
Löhnert, Ulrich

University of Cologne

loehnert@meteo.uni-koeln.de

Advancing synergistic remote sensing applications in the cloudy atmosphere

In the last ~10 years, ground-based remote sensing observatories for have been established in many places over Europe and the U.S.A. So-called supersites, have at minimum a cloud radar, a microwave radiometer, a backscatter lidar and wind profiler/Doppler lidar to retrieve thermodynamic and dynamic structure of the clear & cloudy atmospheric column. However, some measurements are attenuated by clouds, others have a very low vertical resolution, and again others are only very indirectly related to the desired meteorological variable. Thus, a clear picture of the atmospheric column can only be obtained by combining complementary measurements of different sensors, including satellites. Synergy can be realized in different ways, i.e. by taking the available variables from each instrument and combining them in a logical decision process for the derivation of further variables (i.e. Cloudnet algorithm for cloud type classification) or by running a variational retrieval so the that derived quantitative measures (i.e. cloud water content, temperature etc..) match the measurements via a forward model. While these types of synergistic approaches seem obvious and such techniques possess high potential for improving climate models, they have hardly been exploited so far. By giving specific examples obtained within HD(CP)2, but also in the scope of other European research initiatives such as ITARS or ACTRIS, we will show the added value and highlight the potential of an efficient synergy of different ground-based remote sensors, together with satellite observations and corresponding a priori constraints. Progress encompasses variational retrieval studies for improving cloud water content, effective radii through cloud radar and microwave radiometer as well as for obtaining total water content below, within and above the cloud from water vapor lidar and microwave radiometer synergy. In addition to the common Cloudnet algorithm, an advanced method for drizzle onset detection is derived as well as a statistical characterization of boundary layer clouds regarding their coupling to the surface and geometrical extent. Satellite measurement above ground-based stations also provide a more complete picture of the atmospheric column, i.e. by increasing the number of degrees of freedom for signal for temperature and humidity profiles and thus also increasing the potential to predict atmospheric instability.
A Percolation Model for the Scaling of Cloud Size Distributions

Cloud size distributions have been found to show power-law scaling for varying ranges of cloud sizes in a number of observational as well as numerical studies. Many of these studies also showed that most of the larger clouds consist of multiple cells. We propose to explain the observed scaling by a simple 2D continuum percolation model. In continuum percolation, a number of identical discs are randomly distributed within a domain and all overlapping discs are counted as clusters. We adapt the standard model in two points to make it more similar to cloud fields. First, the area of cells is drawn from an exponential distribution and second, as clouds will favor the formation of new clouds in their surrounding, the discs are not distributed in a completely random way but show a tendency to cluster. Despite these changes, we find that our model behaves as predicted from standard percolation. In particular, the size distribution of the resulting clusters strongly depends on the fractional area covered by the discs. For small coverage-fraction, the distribution will follow a power-law for small cluster sizes while the distribution for large cluster sizes is described by an exponential. Approaching a critical coverage, an increasing range of cluster sizes will be described by a power-law. While the parameter of the power-law as well as of the exponential vary with cloud fraction, they are within the same range of values observed in previous studies. In addition, the gradual change of the functional relation with cloud fraction might explain why different authors have found single and double-power-law relations. The predictions of the model are tested with high resolution cloud simulations and satellite data.
Macke, Andreas

*TROPOS*

macke@tropos.de

**HOPE - Example results and first conclusions**

A summary of the measurements performed during the HD(CP)² Observational Prototype Experiment HOPE will be provided. Highlights from "Golden Days" for surface energy budget observations, boundary layer flux and aerosol/cloud measurements as well as results from remote sensing of clouds and aerosols are discussed. HOPE has been designed to provide a critical model evaluation at the scale of the model simulations. Exemplary comparisons between model results and observations will be shown. First conclusions concerning the potential and limitations of the intense joint measurements efforts are critically discussed.
Marschalik, Patrik

*Johannes Gutenberg University Mainz*

[patrik.marschalik@uni-mainz.de](mailto:patrik.marschalik@uni-mainz.de)

**Impact of nucleation rates on ice crystal number concentrations in cirrus clouds**

Ice clouds in the tropopause region, so-called cirrus clouds are important regulators of Earth’s energy budget. However, in contrast to liquid water clouds, the impact of cirrus clouds on radiation is quite unclear. In fact, the sign of the net effect is not known yet, since albedo effect and greenhouse effect are of comparable size, modulated by microphysical properties of ice crystals. Size and number concentration of ice particles determine in first order the radiative effects. For the low temperature regime (T lower than 235K) we can assume that homogeneous freezing of solution droplets is the dominant formation pathway of ice crystals. This process is determined by a nucleation rate, which is very sensitive to environmental conditions (temperature and humidity), whereas the nature of the dissolved matter plays a negligible role. A standard formulation of the nucleation rate is available as a fit to experimental data; the logarithm of the nucleation rate can be expressed as a third order polynomial of the difference of water activities. Some issues appear with this representation. For analytical investigations (e.g. multiple scale asymptotics) this formulation is not very adequate. On the other hand, it is not really clear how details of nucleation rates affect ice crystal number concentrations in bulk parameterizations, i.e. how detailed the formulation of nucleation must be for physically meaningful results. We present new analytic fits for nucleation rates of homogeneous freezing of aqueous solution droplets for ice cloud research in the tropopause region and investigate the impact of different approximations of nucleation rates on ice crystal number concentrations in bulk model parameterizations. Our simulations suggest that for bulk parameterizations our simple formulation of the nucleation rate is a very good and much simpler approximation. This new formulation might be of interest for weather and climate models. (Together with Peter Spichtinger)
Marsham, John

NCAS, University of Leeds

J.Marsham@leeds.ac.uk

The role of moist convection in the West African Monsoon system

Moist convection is integral to the West African monsoon (WAM) system, but until recently computational limits have made analysis of its role very challenging. Now, recent advances in computing, combined with new observations from this highly data-sparse region, have now provided many new insights. Moist convection provides most rainfall in the WAM region, with many organised mesoscale systems over the Sahel, and less organised convection closer to the coast. Multi-day continental-scale simulations of the WAM that explicitly resolve moist convection, show how representing convection explicitly allows greater latent and radiative heating further north, with latent heating later in the day. This weakens the Sahel-Sahara pressure gradient and the resultant flow of moisture into the Sahara, delaying its diurnal cycle and changing interactions between the monsoon and dry boundary-layer convection. This changes the water budget of the whole WAM system. Furthermore, in explicit runs, cold storm outflows provide a significant component of the monsoon flux. These insights provide new understanding of long-standing biases in operational global models. The results demonstrate that improved parameterisations of convection that better capture storm structures, their diurnal cycle and rainfall intensities will therefore substantially improve predictions of the WAM. These model-based insights are supported by analysis of recent field campaign data. These show that the representation of cold-pools is the major cause of biases in global forecasts for the summertime Sahara, with subsequent impacts on the radiative budget, and that the role of cold-pools over the Sahel changes with the seasonal evolution of the monsoon and the energy available to such downdraughts. Finally, we demonstrate how large systematic disagreements between meteorological analyses of the WAM are consistent with errors caused by moist convection, demonstrating the need for both improved representations of convection and the need for improved routine observations from the region.
Maurer, Vera
Karlsruhe Institute of Technology
vera.maurer@kit.edu

Turbulence characteristics in the cloud-free and cloud-topped boundary layer

In spring 2013, extensive measurements with several Doppler lidar systems were performed during the HOPE campaign. They were standing at three locations about three kilometers apart in a moderately flat, agriculturally-used terrain. In a first step, cloud-free convective days were selected. Vertical velocity variance profiles were computed for all locations. On average, normalized profiles agreed well with those found in literature, meaning that the strength of variance is predominantly determined by buoyancy and with that, by surface sensible heat fluxes. Investigating spatial differences, statistical errors as well as the influence of different averaging periods was considered. On average, spatial differences were within the expected range. However, individual time periods with statistically significant spatial differences were found, which could partly be explained by organized structures of turbulence. In a second step, days with boundary-layer clouds were identified. Cloud base heights at three locations were derived from backscatter profiles of the lidar instruments. Again, variance profiles were computed, this time considering cloudy and cloud-free periods. Vertical velocity measurements from a cloud radar were used additionally, which can also provide data within thicker clouds. Variance profiles for cloudy days differed strongly from those on cloud-free days, indicating strong mixing below cloud base. Spatial differences will be investigated as well and compared to those on cloud-free days.
Mauritsen, Thorsten

Max Planck Institute for Meteorology

thorsten.mauritsen@mpimet.mpg.de

Top-down approaches to modeling clouds and precipitation in climate models

Climate models are applied to a range of problems and are used as tools to gain, or demonstrate, understanding. For these purposes it is often perceived important that the results of the model resemble the observed real world to a certain extent. However, even a property as seemingly trivial as the observed global mean temperature is not to be considered a bottom-up result of detailed process modeling and advanced numerical methods. Instead, several key model properties are achieved through a non-empirical tuning-process whereby decisions concerning parameter settings, model configuration and process development is itself guided by the results of the model. In this contribution I will provide insights into the climate model development process at the Max Planck Institute, with a particular focus on the latest efforts to improve the match to observed historical warming by altering cloud feedbacks, e.g. associated with convective mixing and mixed-phase cloud processes. Thereby, tuning provides new insights into knowledge gaps and could guide future process-based exploration.
Mayer, Bernhard

*Ludwig-Maximilians-University Munich*

bernhard.mayer@lmu.de

**Why do we think that radiation is import for clouds?**

Clouds strongly impact solar and thermal radiation. Vice versa, solar and thermal radiation impact cloud formation and evolution in various ways, with varying level of scientific understanding. Clouds cast shadows on the ground which locally reduces convection and feeds back on cloud structure. Absorption and emission of solar and thermal radiation cause a strong warming or cooling close to the cloud edges. This source or sink of diabatic heat first affects the droplets: E.g. latent heat released by condensation is dissipated much more rapidly if thermal emission is considered in addition to heat conduction. In consequence, droplets close to the cloud edges may grow much more rapidly than in absence of radiation. In addition to microphysical effects, radiative heating and cooling also affects dynamics which is commonly expressed through heating and cooling rates. Most of these effects are poorly quantified, mainly due to the high computational cost of radiation calculations in cloud models. This is particularly true if three-dimensional radiative transfer is considered. With increasing model resolution, however, an adequate treatment of radiation becomes more and more important. An overview of radiative effects is given as well as an outline what we have learned in HD(CP)2.
Meyer, Bettina

ETH Zurich

bettina.meyer@erdw.ethz.ch

Employing Non-local Second Order Cumulant Expansion as a Closure Scheme for Boundary Layer Turbulence and Convection

In general circulation models (GCMs), atmospheric boundary layer processes such as turbulent fluxes of entropy and specific humidity cannot be resolved explicitly but must be represented by parameterization schemes. Most current parameterization schemes truncate the hierarchy of moment equations at first order and use second-order equations to estimate closure parameters, e.g., in local diffusive or non-local mass flux closures. However, truncations of moment equations at second order may lead to more accurate parameterizations. At the same time, they offer an opportunity to take spatially correlated structures (e.g., plumes) into account, which are known to be important for convective dynamics. Here we demonstrate the viability of a spatially nonlocal second-order closure (CE2), obtained by truncating the hierarchy of cumulant equations at second order and neglecting cumulants of 3rd order and higher. To explore the applicability of the CE2 closure, we study characteristics of different turbulence regimes through LES, comparing fully nonlinear LES with quasi-linear (QL) LES, in which interactions among turbulent eddies are suppressed but nonlinear eddy—mean flow interactions are retained, as they are in the CE2 closure. In physical terms, suppressing eddy—eddy interactions amounts to suppressing, e.g., interactions among plumes, while retaining interactions between plumes and the environment (e.g., entrainment and detrainment).

That is, the CE2 closure explicitly resolves entrainment and detrainment, obviating the need to parameterize them. First results show that a QL simulation is able to capture important properties of dry convective boundary layers: The well-mixed nature and the rate of growth of the deepening boundary layer are well captured, without the need to introduce closure parameters. Furthermore, instantaneous flow fields reveal that the plumes and their vertically coherent structures are well represented. We will also report results of simulations of moist boundary layers, such as the BOMEX intercomparison case. A computational disadvantage is that solving the resulting equations for the second-order cumulants numerically in general is costly. We will be discussing ways in which additional assumptions (e.g., about horizontal correlation structures among turbulent fields) may lead to closures that are computationally efficient, yet more accurate than existing closures.
Miltenberger, Annette

ICAS University of Leeds

a.miltenberger@leeds.ac.uk

Vertical redistribution of moisture and aerosols in orographic wave clouds (ICE-L)

Ice nucleation and cloud droplet freezing are two of the most poorly constrained cloud microphysical processes in the atmosphere. Orographic wave clouds at mid-tropospheric levels provide an ideal testbed to study these processes by combining aircraft measurements and numerical modeling. In the presented work we investigate wave clouds observed over the Rocky Mountains during the ICE-L campaign using the Unified Model. The thermodynamic and dynamic properties of the wave clouds are extremely well captured in the simulations, which allows us to focus on the representation of cloud and aerosol processes. Cloud microphysics are represented with the newly developed CASIM microphysical scheme, which accounts for aerosol processing and vertical transport. We evaluate the performance of different ice nucleation parameterizations in representing the measured microphysical evolution. In addition the vertical redistribution of aerosol particles due to sedimenting ice crystals is investigated. This comparison provides important insights in our current understanding of cloud droplet freezing and ice nucleation and the role of mid-tropospheric clouds to redistribute aerosol particles.
Miltenberger, Annette

ICAS University of Leeds
a.miltenberger@leeds.ac.uk

Characteristic non-dimensional numbers for orographic precipitation

Several dynamical and microphysical factors determine the precipitation amount originating from a stable orographic cloud. In this study we show that the changes in precipitation efficiency can be described with a set of non-dimensional control parameters. The most important of these is an analogue to the first Damköhler number, i.e. the ratio of advection time to the microphysical timescale of the cloud. These timescales have been investigated with a Lagrangian analysis of orographic clouds in 2D simulations. Analytical approximations are developed and it is shown that after a suitable integration of properties from a vertical stack of trajectories, a unique relation between the precipitation efficiency of orographic clouds and the bulk Damköhler number exists. This scaling relation allows to separate “regimes” in which the precipitation output is very sensitive to aerosol perturbations and such in which the precipitation efficiency is solely controlled by the flow dynamics and the geometry of the cloud. In addition to identifying a small set of non-dimensional characteristic numbers, this approach hence allows to shed more light on the sensitivity of orographic cloud systems to aerosol perturbations in different dynamical settings. As long-term goal this approach could lead to the development of a parametrization of sub-grid orographic precipitation for global climate models.
Moseley, Christopher

Max Planck Institute for Meteorology

christopher.moseley@mpimet.mpg.de

Impact of convective self-organization on precipitation extremes

Observational evidence points to an increase of convective precipitation intensity with temperature beyond the Clausius-Clapeyron rate of 7%/K, ruling out basic thermodynamics as a null-model. We perform large eddy simulations (LES) of the convective dynamics by imposing an idealized diurnal cycle of surface temperature. Convective events interact and self-organize, increase in intensity and area throughout the day, and largest intensities occur far later than the peak in rain area. Using a tracking algorithm, we follow event histories throughout their life cycles, and find that colliding events react strongly to changes in boundary conditions, e.g. increased surface temperature, while solitary events remain unaffected. Intensification can also be reached by unchanged mean temperature but allowing more time for self-organization. This suggests, that the convective field as a whole acquires a memory of past precipitation and inter-cloud dynamics, driving precipitation intensity. Our results imply that convective precipitation intensities result from dynamical interactions between clouds. Temperature increase is only one way how greater interaction can be achieved. The findings may have implications for the diurnal cycle of convection and its parameterization in large scale models.
Evidence for Convective Invigoration from A-Train Observations

The 'convective invigoration' hypothesis posits that aerosol affects precipitating clouds by delaying the onset of precipitation until the cloud has grown above the freezing level, making more efficient ice-phase precipitation processes available and leading to more intense precipitation than would have been produced by the same cloud in a less polluted atmosphere. In the IPCC AR5, evidence for a systematic aerosol effect on precipitation intensity (i.e., not limited to individual storms) is described as 'limited and ambiguous'. We use a combined dataset of spaceborne radar (CloudSat) and lidar (CALIPSO) retrievals of precipitation and cloud thermodynamic phase to derive a climatology of rain occurrence from liquid-phase cloud ('warm rain') and ice-phase cloud ('cold rain'). The cloud-top phase of precipitating cloud serves as a proxy for rain intensity, with warm clouds preferentially producing drizzle and cold clouds preferentially producing more intense rain. This proxy is useful over land, where CloudSat does not retrieve precipitation intensity. In conjunction with aerosol data, the cloud-top phase can be used to test convective invigoration; according to the hypothesis, increasing aerosols should lead to an increase in the cold-rain fraction. We find that warm rain is extremely rare over the extratropical continents (1.5% of rain occurrences). Warm rain is rarer in the most polluted tercile of observations (measured by reanalysis dry AOD) over wide areas of land and ocean outside the tropics, consistent with expectations under the convective invigoration hypothesis. (In the tropics, the effect is reversed, presumably due to wet scavenging.) Extrapolating the observed relationship between warm-rain fraction and reanalysis dry AOD to preindustrial conditions shows a large anthropogenic aerosol influence on precipitation over the extratropical continents. We propose this as evidence supporting the convective invigoration hypothesis.
Müller, Andreas

Naval Postgraduate School

amueller@anmr.de

Towards efficient cloud simulations on petascale supercomputers using the atmospheric model NUMA

Theoretical understanding and numerical modeling of atmospheric moist convection still pose great challenges to meteorological research. One of the difficulties is the multi-scale nature of the phenomena involved. In order to minimize the errors high resolution simulations are needed. This requires efficient numerical methods and highly scalable atmospheric models. The authors are developing the dynamical core NUMA which is used within the next-generation weather prediction model NEPTUNE of the US Navy. NUMA is based on spectral element and discontinuous Galerkin methods which allow arbitrary high order and is capable of running middle and upper atmosphere simulations since it does not make use of the shallow-atmosphere approximation. Recently, the authors have shown that NUMA achieves an excellent strong scaling efficiency of 99% on the entire 3.14 million hardware threads of the supercomputer Mira (fifth fastest supercomputer in the world). This allows to run a one day forecast of a baroclinic instability test case at a global horizontal resolution of 3.0km within the time frame required for operational weather prediction. NUMA is also capable of running Large Eddy cloud simulations using subgrid scale parameterizations like the model by Smagorinsky. In this presentation we show first LES results with NUMA at low resolution and we discuss the potential that NUMA offers for very high resolution cloud simulations on petascale supercomputers like Mira.
Muppa, Shravan Kumar

University of Hohenheim

Shravan.Muppa@uni-hohenheim.de

Convective boundary layer observations during HOPE and their comparison with LES

New approaches in convective boundary layer (CBL) turbulence parametrization schemes are needed for accurate predictions of clouds and precipitation in weather and climate models. Therefore, high temporal-vertical resolution measurements of humidity, potential temperature, and vertical wind in the convective boundary layer were made during the HD(CP)² Observational Prototype Experiment (HOPE) campaign in 2013. A new lidar synergy of water vapor differential absorption lidar, temperature Raman lidar from University of Hohenheim and a Doppler lidar from KIT was employed to investigate the theoretical relationships between integral scales, higher-order moments, fluxes and dissipation rates of these variables mainly focusing on the entrainment layer (EL) at the top of the CBL. These equations form the starting point for tests of and new approaches in CBL turbulence parametrizations. A novel approach is introduced for measuring the rate of destruction of humidity and temperature variances, which is an important component of the variance budget equations. Profiles of the higher-order moments up to the fourth-order of these variables were derived with high-precision. For accurate analyses of the gradients and the shapes of turbulence profiles, the lidar system performances are very important. It is shown that each lidar profile can be characterized very well with respect to bias and system noise but a constant bias has, of course, no effect on the measurement of turbulent fluctuations. Profiles of latent heat and sensible heat fluxes in the CBL were derived using the eddy correlation technique. 3-Dimensional scans were performed to study the meso-scale variability of dynamics, thermodynamics and moisture and to investigate the small-scale spatial and temporal boundary layer variability as well as shallow convection and cloud formation. It is demonstrated how different gradient relationships can be measured and tested with the proposed lidar synergy. The results were then used to evaluate the current large eddy simulation (LES) outputs from ICON, PALM, DALES and UCLA. Finally, an outlook to the next HD(CP)²phase will be given in which the influence of the soil-vegetation continuum on land-surface-atmosphere feedback is studied.
Abstracts

Myagkov, Alexander

TROPOS

myagkov@tropos.de

Determination of shape and orientation of ice crystals in mixed-phase clouds based on observations from polarimetric cloud radar

A continuous estimation of ice-crystal shape in mixed-phase clouds is one of the major problems in the remote sensing of the atmosphere. First, knowledge about the shape allows for improving the accuracy of the existing size and concentration retrievals based on vertical observations from a cloud radar and a lidar. Second, in current weather prediction models the assumed shape of ice crystals defines the mass-area-terminal velocity relationship and the depositional growth rate of ice particles. Third, information about the ice shape enables a continuous estimation of ice-particle size distribution based on complete Doppler spectra measured by vertically pointed cloud radars with the use of known size-velocity dependencies. Fourth, measuring profiles of particle shape allows to draw conclusions on the evolution of ice particle shape during falling which provides information on the occurrence of secondary ice formation processes or aggregation processes taking place. We employed the newly developed 35-GHz cloud radar of type MIRA-35 with the hybrid polarimetric mode to estimate shape and orientation parameters of ice crystals in mixed-phase clouds by comparing observed polarimetric parameters with those calculated with the use of available spheroidal scattering models. In here we present several case studies based on measurements from the field campaign ACCEPT (Analysis of the Composition of Clouds with Extended Polarization Techniques). The measurements took place at the CESAR site, Cabauw, Netherlands, in October – November 2014. All the presented cases correspond to observed clouds with different temperatures between -5 and -25°C. We also show that the retrieved shape is in a good agreement with long-term laboratory studies on the ice crystals grown above water saturation in free-fall chambers.
A Lagrangian drop model to study the evolution of the raindrop size distribution in shallow cumulus

Despite the ever increasing grid resolution, understanding precipitation remains one of the major challenges in numerical weather prediction as well as climate modeling. To investigate warm rain microphysical processes on a particle-based level, we introduce a Lagrangian drop (LD) model to simulate raindrop growth in shallow cumulus. The LD model is one-way coupled with a Eulerian LES and represents all relevant rain microphysical processes such as evaporation, accretion and selfcollection among LDs as well as dynamical effects such as sedimentation and inertia. To test whether the LD model is fit for purpose, a sensitivity study for isolated shallow cumulus clouds is conducted. We show that the amount of surface precipitation and the slope of the raindrop size distribution are sensitive to the representation of selfcollection in the LD model. Overall, sensitivities of the LD model are small compared to the uncertainties in the assumptions of commonly used bulk rain microphysics schemes. Therefore, the LD model is well suited for particle-based studies of raindrop growth and dynamics. We apply the LD model to study the development of the raindrop size distribution in individual shallow cumulus clouds. We show that the shape of the raindrop size distribution depends on the stage of the lifecycle of the cloud. Closure assumptions currently used in bulk rain microphysics parameterizations, which have been developed for more heavily precipitating cases, are not appropriate for shallow cumulus. Although we find a relation of the shape parameter to the mean raindrop diameter for individual shallow cumulus clouds, this relation differs already for the two clouds considered. It is therefore doubtful whether a two-moment scheme with a diagnostic parameterization of the shape parameter, i.e., a local closure in space and time, can be sufficient, especially when being applied across different cloud regimes.
Exploring bin-macrophysics models for moist convective transport and clouds

This study explores a mass flux framework for moist convective transport and clouds that is formulated in terms of discretized size densities. The properties of each bin in these histograms is estimated individually, making use of a rising plume model. In this framework, the number density acts as a weight, appearing in the area fraction of the mass flux. Such “bin-macrophysics” models have the benefit that bulk closures become redundant, and that scale-awareness is introduced at the basis of the formulation. Large-eddy simulation results are used to justify the design of this framework and to constrain associated constants of proportionality. The behavior of the framework is explored by means of single-column model simulations of various idealized cases of shallow and deeper surface-driven convection. A smoothly developing solution for a deepening marine shallow cumulus case is obtained, reproducing key aspects of transport and clouds that define this regime. Further investigation of the size statistics of the framework reveals that indirect interactions between resolved bins play a key role in the equilibration process. An “acceleration-detrainment” layer is identified above cloud base in which the flux uptake by the largest plumes is counteracted by the detrainment by decelerating smaller plumes. This suppresses CIN, and thus acts to preserve the cloud-subcloud coupling. The convective mass flux shows sensitivity to environmental humidity in the deeper convective cases, reproducing transitions from shallow to deep convection. Sensitivity tests are performed to assess the impact of various components of the framework.
Noda, Akira

JAMSTEC

a_noda@jamstec.go.jp

High cloud size dependency in the applicability of the fixed anvil temperature hypothesis using global non-hydrostatic simulations

The applicability of the fixed anvil temperature (FAT) hypothesis is examined using data of a global non-hydrostatic model, focusing particularly on high cloud size dependency. Decomposition of outgoing-longwave radiation (OLR) into three components, including cloud-top temperature (TCT), upward cloud emissivity (ε), and clear-sky OLR (FCLR), reveals that the relative contributions of these three components to changes of OLR are highly dependent on cloud size. That is, the FAT hypothesis is applicable only to smaller clouds, because the contribution of TCT by those clouds is small, and ε is more important. In contrast, for larger clouds, the contribution ε is comparable to that of TCT, and thus, both components are equally important. FCLR substantially reduces OLR, but shows dependence on cloud size.
Nuijens, Louise

MPG

louise.nuijens@mpimet.mpg.de

Observed and modeled sensitivity of trade-wind cloudiness to changes in the large-scale flow

Large areas over subtropical and tropical oceans experience neither strong subsidence nor strong ascent. In these regions shallow trade-wind clouds prevail, whose vertical distribution has emerged as a key factor determining the sensitivity of our climate in global climate models. But how susceptible are trade-wind clouds in our current climate? Do we understand the role of the large-scale flow in variability in these clouds? And do global models represent those patterns of variability?

In this talk I will show how ground-based and space-borne remote sensing, combined with Large-Eddy Simulation, start to answer these questions and help validate climate models. The results reveal an important role for the deepening of cumuli in influencing variability in low level cloudiness. By suppressing surrounding clouds, deeper clouds can lead to less cloudiness overall, such as is true in regions near tropical deep convection. But also in regions with mean subsidence, the presence of deeper shallow cumuli can change low-level cloudiness substantially. This mesoscale variability explains, in part, why cloudiness is poorly predicted by large-scale factors on time scales less than a month. Additionally, subtle combinations of large-scale dynamic and thermodynamic factors, as well as interactive radiation, are required to produce the stratiform outflow layers near cumulus tops that can substantially increase low-level cloudiness. This suggests that although mesoscale variability plays an important role, we should be mindful of how the large-scale flow conditions the lower atmosphere.

Global models underestimate the strength of these relationships and diverge in particular in their responses to large-scale vertical motion. I will discuss how these results relate to climate change studies, which hint at the importance of the shallowness of the cloud layer and vertical moisture mixing in explaining the spread in climate sensitivity.
Orlandi, Emiliano

*University of Cologne*

eorlandi@meteo.uni-koeln.de

**Overlap statistics of shallow boundary layer clouds: comparing ground-based observations with large-eddy simulations**

As large-scale models for weather and climate have coarse spatial resolutions, they cannot resolve clouds within a vertical grid column and thus rely on parameterizations, leading to uncertainty in the representation of clouds and the way they overlap in the vertical. The uncertainty in the cloud overlap parameterization remains a significant source of error in the Earth's radiation budget in general circulation models (GCMs). Most studies concerning cloud overlap mainly focused on either large ensemble of cloud types or deep convective cloud fields. Cumuliform boundary layer cloud fields have been less researched despite the fact that their irregularity in shape and in spatial distribution at subgrid scales can impact the cloud overlap significantly. In this study, high-resolution ground-based measurements are used to assess the realism of fine-scale numerical simulations of shallow cumulus cloud fields. The overlap statistics of cumuli as produced by i) local large-eddy simulations (LES) as well as ii) the big-domain ICON at cloud resolving resolutions are confronted with CloudNet datasets at the Jülich ObservatorY for Cloud Evolution (JOYCE). Cloud fraction masks are derived for five different cases during the April-August 2013 period, using gridded time-height datasets at various temporal and vertical resolutions. The overlap ratio (R), i.e. the ratio between cloud fraction by volume and by area, is studied as a function of the vertical resolution. Good agreement is found between R derived from observations and simulations. Simulated and observed decorrelation lengths are smaller (< 300 m) than previously reported (> 1 km). A similar diurnal variation in the overlap efficiency is found in observations and simulations. The inefficient overlap we found at sub-grid vertical scales has the potential of significantly affecting the vertical transfer of radiation, yet few GCMs take such overlap at small, unresolved scales into account. A better understanding of the unresolved cloud overlap now opens the door for parameterizations where cloud overlap is better grounded in physics.
Towards simultaneous retrieval of water cloud and drizzle using ground-based radar, lidar and microwave radiometer

Correct representation of clouds and their interaction with the surrounding matter and radiation are one of the most important factors in climate modelling. In particular, feedback processes involving low level water clouds play a significant role in determining the net effect of cloud climate forcing. An accurate description of cloud physical properties is therefore necessary to quantify these processes and their implications. To this end, measurements combined from a variety of remote sensing instruments at different wavelengths provide crucial information about the clouds. In order to exploit this, building upon previous work in this field, we have developed a ground-based multi-sensor retrieval algorithm within an optimal estimation framework. The inverse problem of mapping the radar, lidar, and microwave radiometer measurements into retrieval products is formulated in a physically consistent manner, without relying on approximate empirical proxies (such as explicit liquid water content vs radar reflectivity factor relationships). Given temperature, humidity profiles, measured signals, a priori constraints and assuming a mono-modal gamma droplet size distribution, the microphysical properties of the cloud in question are derived. The algorithm was successfully tested using synthetic signals based on the output of large eddy simulation model runs. It is being applied to the data collected during the recent ACCEPT observational campaign in Cabauw, The Netherlands. The algorithm is being expanded to allow for the simultaneous retrieval of both cloud and drizzle microphysical parameters.
Panosetti, Davide

ETH Zurich

davide.panosetti@env.ethz.ch

Idealized convection-resolving and large eddy simulations of moist convection over mountainous terrain

Convection-resolving models (CRMs) at a horizontal resolution of O(1 km) have led to major improvements in both numerical weather prediction and climate simulations in recent years. However, issues still remain in simulating the diurnal cycle and distribution of clouds and precipitation. Open questions are left regarding the turbulence parameterization and the treatment of shallow convection in CRMs. These tasks become even more challenging over mountainous terrain, where orographic circulations exert a strong local control on the triggering of convection. This study compares the mechanisms of convection initiation and precipitation development within thermally-driven orographic circulations in idealized CRM and large eddy (LES) simulations. First, LES at a horizontal grid spacing of 200 m is employed to analyze the development of the orographic circulations and associated clouds and precipitation. Second, CRM simulations are conducted to evaluate the performance of a kilometer-scale model in reproducing the discussed mechanisms. Third, the behavior of different turbulence schemes and a shallow convection parameterization in CRMs is documented. The timing and spatial distribution of clouds and precipitation is largely controlled by the interplay between small-scale vertical mixing processes and horizontal moisture transport by the orographic circulations. In the CRM simulations, the spatial distribution of clouds and precipitation is generally well captured. However, the transition to deep convection occurs faster, and precipitation is generated earlier and in higher amounts compared to LES, as reduced vertical mixing increases horizontal convergence at the mountain summit in the CRM simulations. The choice of the turbulence and shallow convection parameterization in CRMs has a minor influence on the spatial distribution of precipitation. However, it changes the amount of vertical mixing and the strength of the orographic circulations, thereby influencing the onset time of convective precipitation.
Convective Parameterization In a 2.5 km NWP Model: Improvements of Summer Precipitation Diurnal Cycle

A new high resolution Global Environmental Multiscale (GEM; Côté et al.) model version is currently developed at Environment Canada as part of the next operational High Resolution Deterministic Prediction System (HRDPS, Mailhot et al., 2010) with an horizontal grid-spacing of 2.5 km. At this resolution, the question of using or not a convective parameterization (CP) remains. Continental precipitation diurnal cycle is a critical aspect of numerical weather prediction: when no CP is applied, delayed precipitation is often seen even at 2 km grid-spacing (Xu et al. 2002). Moeng et al. (2010) have shown that models with horizontal grid-spacing of the order of km are missing important part of subgrid-scale moisture vertical fluxes throughout the deep convective layer. However, CP were generally developed for lower resolution models with hypotheses (i.e. convective quasi-equilibrium, local compensating subsidence) that are not always valid at the km scale. New approaches are proposed to relax those constraints (e.g. Arakawa et al., 2011, Kuell and Bott, 2008). The Kain-Fritsch CP (Kain and Fritsch, 1990, 1993) is already used in two GEM versions with grid-spacing of 25 and 10 km (Charron et al. 2012). It has been adapted for the HRDPS and tested over a Pan-Canadian domain for 20 summer cases of 48h simulations. It will be shown that, when using the adapted Kain-Fritsch CP, a reduction in diurnal cycle biases is seen, particularly for large precipitation events, while it doesn't degrade other surface skill scores, except for trace precipitation bias. A squall line case will be presented against observations, to illustrate how the precipitation timing, intensity and structure is modified with the use of Kain-Fritsch and how the atmospheric vertical profile is sensitive to the different Kain-Fritsch parameters.
Pawlowska, Hanna

*University of Warsaw*

hanna.pawlowska@igf.fuw.edu.pl

**Towards a new concept in cloud processes modeling**

A new numerical model for studying aerosol processing by clouds is being developed at the University of Warsaw. It responds to the need for the development of effective tool for research of aerosol processing by clouds, for which even the most sophisticated traditional cloud microphysics approaches are either inadequate or impractical.

The newly developed model’s modules couple an efficient description of cloud dynamics (EULAG’s MPDATA-based anelastic framework) with a novel treatment of aerosol-cloud-precipitation microphysics (the Super-Droplet method) within a robust numerical modeling tool. Neither MPDATA-based anelastic solvers, nor particle-based microphysics modules are commonly available in presently developed models for cloud research, partly owing to the complexity of those algorithms.

The new development is carried out in compliance with free and open source software engineering practices employing modern coding techniques.
Peters, Karsten

*Max Planck Institute for Meteorology*

karsten.peters@mpimet.mpg.de

**Coupling the Stochastic MultiCloud Model to ECHAM6.3 improves simulated tropical intraseasonal variability**

An adequate representation of convective processes general circulation models (GCMs) remains one of the grand challenges in atmospheric science. In particular, the models struggle with correctly representing convection associated tropical intraseasonal variability. We use observations of tropical convection obtained from high resolution rain radar to inform the design of a novel convection parameterisation with stochastic elements. The scheme is built around the Stochastic MultiCloud Model (SMCM, Khoudier et al 2010). We utilize the SMCM-based estimates of deep convective area fractions (CAF) per model grid box as part of the deep convection scheme of a GCM. The SMCM predicts CAFs given the large-scale environment, which in our case is given by vertical motion and relative humidity at 500 hPa. The CAFs are used to estimate the cloud base mass-flux in the closure assumption of convective mass-flux schemes. The closure of the convection scheme thus i) receives a stochastic component, potentially improving modelled convective variability and coherence, and ii) is not anymore based on the common assumption of convective equilibrium at the grid-box scale, i.e. the depletion of buoyancy (CAPE) given a certain time scale. We apply this approach to the operational convective parameterisation of the ECHAM6.3 GCM. We perform 30-year AMIP simulations as well as 1 month long integrations with model output at every timestep. We find that through coupling the SMCM to ECHAM6.3, it displays a substantially improved simulation of tropical intraseasonal variability. Especially the simulation of Madden-Julian-Oscillation and Kelvin-Wave type features improves upon the standard model version and compares well to observations. We attribute these improvements to an overall decrease of convective mass-flux, a more realistic relationship between precipitation and the vertical moisture distribution and increased organization of convection. These improvements go in hand with some, albeit small changes in the mean global climate.
Peters, Karsten

*M*ax Planck Institute for Meteorology

karsten.peters@mpimet.mpg.de

**Effects of the land surface on pre-existing organized convective systems**

An adequate representation of convective processes in numerical models of the atmospheric circulation remains one of the grand challenges in atmospheric science. This holds for simulations performed with climate as well as numerical weather prediction models. In particular, the correct representation of the coupling between atmospheric convection and the underlying land surface remains a challenge – the coupling is assumed to be strong, but past efforts in determining its strength have suffered from methodological limitations, e.g. due to poorly resolved convective processes in models with resolution >1km. Here, we utilize ICON across a range of resolutions (cloud system resolving down to LES) to investigate the impact of the land surface on pre-existing mesoscale convective systems. Idealised model setups are employed to first spin-up a mesoscale convective system without allowing for interaction with the underlying surface, i.e. surface heat fluxes are fixed. Then, the fully developed convective system is exposed to altered surface fluxes and a fully interactive land-surface scheme. We focus our analysis on the effects on the dynamics of the convective system, such as propagation, organization and overall intensity. Preliminary results suggest that effects of the altered land-surface properties are mainly manifested in altered cold-pool properties, which show to have a pronounced effect on the characteristics of the convective system. Results from a suite of sensitivity experiments will be presented and the potential to exploit these results for model development will be illustrated.
Radar observations of ice particle growth along fall-streaks within mixed-phase clouds

Within mixed-phase clouds the interaction of ice crystals with super-cooled liquid water leads to an enhanced growth of the ice particles. The growth of ice particles during the interaction is an important process for precipitation formation in the mid-latitudes. Nowadays the interaction is still not clearly understood. To understand the ice particle growth within such clouds the microphysical changes of a single particle population along its way through the cloud have to be analysed. A way to study changes in ice particle micro-physic is to analyse radar Doppler spectra. Using the 3 beam configuration of the Atmospheric Transportable Radar (TARA) we retrieve the full 3-D Doppler velocity vector. This dynamical information is used to retrieve the back trajectory of a measured population of particles. Now microphysical changes along the trajectory can be studied. Therefore, the retrieved spectrograms along such trajectories offer a new perspective for cloud microphysical studies. Microphysical changes along the path of a population of particles through a cloud are represented in the retrieved spectrograms. The instrumental synergy during the ACCEPT campaign (Analysis of the Composition of Clouds with Extended Polarization Techniques campaign), Fall 2014, Cabauw the Netherlands, make it also possible to retrieve liquid water layers within mixed-phase clouds. Therefore, identified changes within the retrieved spectrograms can be linked to the presence of super-cooled liquid water layers. In this work we will explain the backtracking methodology and show the impact on interpretation of velocity spectra. The application of this new methodology for ice particle growth process studies within mixed-phase clouds will be discussed.
Piaget, Nicolas

ETH Zurich

nicolas.piaget@env.ethz.ch

Sensitivity of extreme precipitation in Switzerland to atmospheric processes

Dimensioning of flood protections is based on the estimation of the probable maximum flood (PMF). A reliable estimate of this quantity can only be made using a realistic estimate of the probable maximum precipitation (PMP) in the considered catchment. However, traditionally used procedures to estimate the PMP are not well suited for mountainous regions. The complex terrain does strongly affect the precipitation distribution and impose strong nonlinearities for the precipitation resulting from small variations in the atmospheric flow conditions. Therefore, an in-depth knowledge of the precipitation characteristics of a catchment is needed to obtain realistic estimates of the PMP and eventually the PMF. We use the high-resolution numerical weather prediction model COSMO to study small-scale processes induced by topography-flow interactions. A sensitivity analysis is performed to determine the influence of subtle variations in atmospheric parameters such as specific humidity, wind direction, and temperature on the precipitation distribution. For this purpose, various approaches are used to modify either the initial and boundary conditions of humidity and temperature. Simulations are performed for different flood events in Switzerland, including different type of synoptic forcing, such as blocked and unblocked cases, characterized by atmospheric rivers or quasi-stationary cyclone. The results show that, for instance an increase of the specific humidity of the incident flow does not necessarily produce an increase of precipitation in the target catchment. Indeed, with increased ambient moisture, smaller mountains upstream of the catchment can be more efficient in triggering precipitation and therefore reduce the moisture available downstream. This novel approach with a set of synthetic sensitivity experiments allows estimating, for a particular catchment, the physical limits of the PMP value.
Plesca, Elina

University of Hamburg

elina.plesca@uni-hamburg.de

Constraining Tropical Circulations in Climate Models with Upper Tropospheric Humidity Satellite Data

Authors: Elina Plesca, Verena Grützun, Stefan Buehler

Understanding the impact of climate change on the intensity and physical configuration of the Walker circulation represents a key step in the assessment of changes at global and regional level, specifically in the patterns of clouds and precipitations over the tropical Pacific and the West Pacific Warm Pool. At the same time, there is a large degree of uncertainty in these projections, such as the inability of the models to consistently simulate the recent strengthening in the Walker circulation. This study aims at comparatively investigating the features of the Walker circulation as derived from the CMIP5 model outputs and the existing satellite humidity long data record. For this purpose, we are looking for a correlation between the dynamical features of the tropical circulations and the upper tropospheric humidity (UTH). Buehler and John’s (2005) method of relating microwave radiances to UTH will be used to obtain the observation data set from the microwave retrievals. The same method will be applied to the CMIP5 idealised experiments’ outputs in order to derive a corresponding modelled radiance data set. The comparison of these datasets would constitute a tool in determining the performance of the models in realistically describing the circulation, as well as in pointing out possible biases and expected uncertainties. These results will further be used for the evaluation of the climate model projections for the tropical circulations and identification of features with various confidence levels. References: Buehler, S.A., and John, V.O. (2005), A simple method to relate microwave radiances to upper tropospheric humidity, J. Geophys. Res., 110, D02110
Abstracts

Pospichal, Bernhard

University of Leipzig

bernhard.pospichal@uni-leipzig.de

Conditions for (sub-)adiabatic liquid water content in clouds from supersite ground-based remote sensing observations

The vertical distribution of cloud droplets within a liquid water cloud is an important parameter for assessing the radiative effect of clouds as well as the cloud-aerosol interactions. In order to derive profiles of cloud droplet number concentrations, the liquid water content (LWC) is often assumed to follow an adiabatic increase with height. From observations it is known that in many cases a sub-adiabatic LWC is present, due to entrainment or precipitation processes. Several methods to derive cloud properties, including sub-adiabatic conditions, using different sets of instruments have been described in the literature, but they only present case studies. In this study, we take long-term ground-based cloud observations in the framework of the Cloudnet program to assess the adiabaticity of liquid water clouds, using a combination of cloud radar, microwave radiometer and ceilometer. We will show that the degree of adiabaticity depends on several factors, such as cloud depth, cloud temperature and stability within and around the cloud. This study will provide results from Leipzig, Jülich and other Cloudnet stations in Europe (e.g. Mace Head, Chilbolton, Palaiseau, or Potenza). For several case studies, we will also contrast these observations with satellite observations using products from SEVIRI and MODIS instruments.
Ship Tracks: A framework for aerosol-cloud interaction evaluation in warm-phase stratocumulus at the kilometer scale

Ship tracks are undoubted manifestations of aerosol cloud interactions (ACI) embedded within stratocumulus clouds. Field campaigns of the past 20 years showed them to only occur within a tightly constrained range of environmental conditions. Satellite retrievals have suggested them to be irrelevant for climate, due to their rare global occurrence. However, given the well constrained conditions under which they occur and their horizontal extend of 8-30 km, they pose an ideal platform for kilometer-scale climate models to evaluate ACI in stratocumulus, which generate a large fraction of uncertainty in climate sensitivity. Here we used the COSMO model at 2-km resolution to investigate an episode of observed ship tracks over the Bay of Biscay. We demonstrated that the COSMO model, including two-moment aerosol (Vignati et al 2004) and cloud microphysics (Seifert and Beheng, 2006), captured the essence of ship tracks in a stratocumulus-topped boundary layer (BL) with a cloud top below 700 m. The BL structure was found to be in good agreement with local radiosonde soundings and in-track cloud brightening was simulated in accordance with the MODIS retrieval (Possner et al, 2014, 2015). Furthermore, the simulated cloud microphysical response was found to be within the observed range of responses during various field campaigns. Building upon these results, we further explore the scale-dependence of the involved parameterisations as we approach global climate model resolutions from the kilometer scale. Reduced BL mixing at coarser resolutions impacted the CRE induced by the aerosol. CRE differences up to 163% (7 W/m²) were simulated as the spatio-temporal resolution was reduced from 2 km (20s) to 50 km (180s). Furthermore, in experiments of identical resolution (2 km), but increasingly diluted emissions (down to 50x50 km² emission homogeneity), differences in the mean CRE of 47% were still found. The non-linearity in the latter simulations was attributed to the cloud-radiative coupling.
Preissler, Jana

*National University of Ireland, Galway*

JANA.PREISSLER@nuigalway.ie

**Six years of remote sensing of cloud microphysics at Mace Head, Ireland**

Ground-based remote sensing observations of cloud microphysical properties have been done at the atmospheric research station Mace Head on the West coast of Ireland, since 2009. For this study, homogeneous single-layer non-precipitating water clouds were carefully selected from a data base of more than six years. The 100 selected cloud periods were each about 10 to 30 minutes long. With a temporal resolution of 10 seconds they provided over 16,000 data points, averaged over the cloud depth. In total, 8473 of them were classified as marine, 2386 as marine modified, 4108 as continental and 1721 as continental modified. Generally, the cloud droplet number concentrations (CDNC) were smallest for marine (median of 80 cm\(^{-3}\)) and marine modified (median of 60 cm\(^{-3}\)) air masses. The overall spread of CDNC was largest for continental cases (median of 270 cm\(^{-3}\)). The median was largest for continental modified cases (460 cm\(^{-3}\)). As the CDNC is directly linked to the number of available cloud condensation nuclei, it is expected to have lower CDNC in clean marine air and higher CDNC in polluted continental air. The effective radii in marine and marine modified conditions were higher than in continental modified and continental conditions. The highest median effective radius of 13 μm was found in case of marine modified air masses and the lowest of 6 μm for continental modified cases. The small variations of the liquid water content with air mass were likely due to the studied cloud type and the exclusion of precipitating clouds. The cloud optical depth (COD) was smallest for marine cases. All but the marine distribution of the COD were bi-modal. Overall, the COD was lower in cleaner air masses and higher in more polluted conditions.
Simulations of Boundary Layer Clouds in PyCLES, a Next Generation Large Eddy Simulation Infrastructure

Despite numerous efforts to improve the accuracy of large eddy simulations of stratocumulus clouds, maintenance of realistic cloud cover and liquid water path values in simulations typically relies on the use of high resolution grids with vertical grid spacings near cloud top of only several meters. These resolution requirements and, accordingly, the large computational burden of simulations, have limited the ways in which LES can be used to study clouds in the climate system. The recently developed LES code called PyCLES (Pressel et al., 2015), breaks in several ways with conventional atmospheric LES codes. PyCLES has a number of unique features that affect its computational efficiency, physical formulation, and numerical discretization. Most notably: the software is written in Python, Cython, and C; its parallelization permits three-dimensional domain decomposition; it uses specific entropy and total water specific humidity as prognostic variables allowing closed entropy and water budgets; and the equations of motion are discretized using state-of-the-art, high-order Weighted Essentially Non-Oscillatory (WENO) schemes. In this talk we will highlight key aspects of the design and show how they contribute to the unique capabilities of PyCLES. We will focus in particular on simulations of boundary layer clouds, including the canonical DYCOMS-RF01 stratocumulus case (Stevens et al., 2005) where we will show that the numerical properties of WENO schemes offer key advantages over more commonly used schemes. Consequently, PyCLES is able to provide faithful simulation of stratocumulus clouds at coarser resolution and thus less computational effort than traditional LES codes.
Protat, Alain

Bureau of Meteorology

A.Protat@bom.gov.au

Tropical convection processes using dual-polarization and dual-Doppler radar observations to inform cumulus parameterization development

Alain Protat (1) and Christian Jakob (2) 1: Australian Bureau of Meteorology, Melbourne, Australia; 2: Monash University, Clayton, Australia

The representation of convective cloud properties in global and high-resolution models is an essential step towards accurate quantitative precipitation forecasts. It has been recently demonstrated that global models tend to produce a reasonably good estimate of the rainfall accumulation, but for wrong reasons (the “raining too little too often” problem). This calls for a better understanding of convective cloud processes and their variability as a function of the large-scale environment. In this talk we will review results obtained on the characterization of tropical convective properties using a research C-band dual-polarization radar (CPOL) located around Darwin, Australia. This talk will highlight (i) the variability of the statistical properties of convective clouds as a function of the large-scale atmospheric “regime”, (ii) the composite life cycle of the cumulus cloud modes and their microphysical properties, (iii) the diurnal cycle, (iv) the mechanisms involved in the transition from shallow to deep convection, with some focus on the role of the congestus stage, and (v) the convective mass flux, its components, and its variability. We’ll finally show how well those processes are currently reproduced by the model and what plans we have to improve the representation of convection in global models.
Overview on HD(CP)² model evaluation

The high-resolved, large-domain HD(CP)² simulations are being evaluated against a broad range of HD(CP)² observations from the HOPE campaign to supersite and full-domain observations. The evaluation task force aims at synthesising the results to characterise the model skill with a focus on the representation of moist processes. The talk will report about the outcome of this evaluation synthesis. NB: quite many HD(CP)² colleagues contribute to the effort, ideally they should appear as co-authors at some level.
Randall, Dave

Colorado State University

randall@atmos.colostate.edu

Chaotic Convection in CAM

It has been suggested that stochastic fluctuations of convective activity can lead to systematic changes in large-scale weather and climate. We present results of recent ensemble-prediction experiments with the super-parameterized version of CAM that provide a new way to explore such effects, without the need for ad hoc assumptions about the nature of the stochastic effects. The results show that the predictability of the super-parameterized convection is organized on the large scale.
Radiative energy flows in the atmosphere: observations versus global modeling

Radiative energy fluxes are simulated in global modeling with the constraint that the global annual averaged net-flux at the top of the atmosphere is close to zero. As processes involving clouds and precipitation are simulated even in the context of identical boundary conditions (e.g. solar input, land surface properties or sea surface temperature) there is significant diversity for energy flux distributions by different global models. Truth at the top of the atmosphere (TOA) is offered by satellite observations and shortcomings of cloud radiative effects (CRE) in global modeling are easily identified. Truth for radiative fluxes at the surface (with coverage better than offered by ground sites) is more difficult. Usually information of complementary satellite retrievals on atmospheric and surface properties are needed and applied to translate TOA signals into surface signals. Such derived surface energy fluxes are often quite different. And netflux imbalances at the surface set the stage for sensible and latent heat release. This presentation explores spatial features of differences between modeled and satellite associated radiative fluxes to better understand differences in global averages.
Reichardt, Isabelle

Karlsruhe Institute of Technology

isabelle.reichardt@kit.edu

Influence of different ice-nucleation parametrizations on simulations of orographic mixed-phase clouds

Clouds play a significant role in the energy budget of Earth. Unfortunately the influence of aerosols on clouds and their radiative characteristics is not sufficiently understood. This can yield high uncertainty in climate and numerical weather prediction models. In this study the influence of different heterogeneous ice nucleation parametrizations which are accounting for aerosol properties is the primary focus. These parametrizations are derived either from field measurements or from laboratory studies. In this study, we evaluate three different state-of-the-art parametrizations, which relate the ice nuclei particle concentration to aerosol parameters. Idealized 2D-simulations of orographic mixed-phase clouds with different surface temperatures are performed. The computational domain has a horizontal resolution of 1km and 60 vertical levels are used. The model used is coupled with a two-moment microphysic bulk scheme, which describes different categories of hydrometeors. It is found that while the parameterizations yield large differences in the number of ice nucleating particles, the resulting differences in the ice mass fraction are surprisingly low, which implies that microphysical buffering mechanisms are operating. Hence we analyzed the conversion rates of all hydrometeors to identify the main processes of this buffering.
Retsch, Matthias Heinz

Max Planck Institute for Meteorology

matthias-heinz.retsch@mpimet.mpg.de

Refining vertical resolution in a GCM

ECHAM-6.3.01 is used to study effects of three different vertical resolutions on convection in the tropics and the structure of the ITCZ. Apart from the default 47 levels resolution, a 76, 134 and 192 levels resolution is tested. Vertical resolution is only refined in the troposphere, i.e. below 50 hPa in the tropics. Simulations are conducted on an aqua planet with equator symmetrical SST and steady equinox conditions. Integration time period is five years, with the first two years as a spin up phase. Most significant change caused by the increase of level number regards the ITZC structure, which turns into a single ITZC in 134 and 192 levels resolutions from being a double ITCZ in the 47 and 76 levels resolutions. Cloud water content at the equator and in 600 hPa triples, indicating that ECHAM’s mixing parametrization could be important in explaining the difference in ITCZ structure. Indeed, when turning off turbulent mixing processes, ITCZs in both the 47 and 192 levels resolutions comprise a double structure. If mixing is turned on, it is amplified when more levels are present, as mixing takes place for a certain amount of air at every level. Therefore more air gets mixed in refined resolutions. This prevents deep convection to develop off the equator as clouds terminate in lower altitudes more quickly. Directly at the equator though deep convection triggers successfully, as with the maximum SST there the surroundings are most favourable. Still, cloud cover shows differing distributions in no-mixing experiments. Cloud cover is an important quantity for the cloud radiative effect. So, clouds are made invisible for long- and short-wave radiation, to cease cloud radiative effect. With this setting, 47 and 192 levels resolutions also show less difference in ITCZ structure, although less than without mixing.
Richard, Evelyne

*French National Center for Scientific Research*

Evelyne.Richard@aero.obs-mip.fr

**Heavy Precipitations Events : Some results from HyMeX**

Coastal regions of the Mediterranean basin are often struck by devastating high precipitation events (HPE), which occur predominantly in autumn. These events are usually associated with slow-moving trough, high CAPE values over the western Mediterranean and a moist troposphere. Low level jets advect moisture from the sea towards the coast, where the HPEs occur. These unstable inflows together with lifting above orography or along convergence lines lead to deep moist convection which can either occur alone or embedded into larger, stratiform precipitation systems.

Considerable efforts have been made in recent years to improve the skill of the forecasts for such severe events and significant progress was obtained thanks to the development of high-resolution convection permitting models. However, society’s demands for predictive quality still remain largely unsatisfied and more accuracy is required, in terms of amount, timing, and location of rainfall. The following explanations are commonly put forward to explain the limited skill of Numerical Weather Prediction (NWP) models: i) inaccuracy of initial and/or boundary conditions, ii) inappropriate representation of some physical processes or their interaction, iii) intrinsic limitations on the predictability of atmospheric flows.

In this talk, the details and relative weight of each contribution are investigated using Meso-NH model output together with observations collected during the 2012 Special Observing Period of the Hydrological cycle in Mediterranean Experiment (HyMeX). Special emphasize is put on the challenging issue of representing in-cloud turbulence at kilometric and sub-kilometric resolutions.
Romakkaniemi, Sami

Finnish Meteorological Institute

sami.romakkaniemi@fmi.fi

Modelling aerosol-cloud interactions with a sectional model for microphysics implemented to a Large-Eddy Simulator

A novel tool for investigating aerosol-cloud interactions in a cloud-resolving model framework is presented. The model represents the key microphysical processes interactively between aerosols and clouds, with particular emphasis on the wet deposition of aerosol particles and condensable gases. The model is built upon a modified version of the UCLALES Large-Eddy Simulator (LES), and an extended version of the sectional microphysics model SALSA that is employed in the ECHAM climate model family. Implementation of the UCLALES-SALSA is described in detail. The extended SALSA presented here also includes cloud droplets and rain with the implementation of relevant microphysical processes. Given our main emphasis, the cloud droplet size bins are defined according to the dry diameter of the condensation nucleus to allow accurate tracking of the aerosol properties during cloud processing. As a setback, some accuracy in terms of precipitation formation is lost, which in part relies on autoconversion parameterization. However, to accurately describe the growth of existing drizzle drops to rain, which is critical for the wet deposition process, unlike the cloud droplets, the precipitation size bins are defined according to the actual drop size. With these additions, the implementation of the SALSA model replaces most of the microphysical and thermodynamical components within the UCLALES. The cloud properties and aerosol-cloud interactions simulated by the model are analysed and evaluated against detailed cloud microphysical boxmodel results and in-situ aerosol-cloud interaction observations from the Puijo measurement station in Kuopio, Finland. The ability of the model to reproduce the impacts of wet deposition on the aerosol population is demonstrated. UCLALES-SALSA will be used to improve the aerosol aging and wet removal representation in large scale atmospheric models and to study conditions where aerosol has high potential in modifying cloud properties.
Romps, David

UC Berkeley
dromps@lbl.gov

What sets the speed of cloud updrafts?

One of the unsolved puzzles in atmospheric science is what sets the speed of cloud updrafts in radiative-convective equilibrium (RCE). The lack of an equation for this velocity scale is a conspicuous reminder that we have no comprehensive theory for RCE, and it is likely that the resolution of the velocity-scale problem will be an essential step in the development of that theory. Here, I report on progress towards an equation for RCE updraft speeds. In particular, large-eddy simulations of RCE are used to develop theories for convective available potential energy (CAPE) and for the drag forces acting on cloud updrafts. I will also discuss some of the remaining obstacles that must be surmounted before a theory for updraft velocities can be formulated.
Rüdisühli, Stefan

ETH Zurich

stefan.ruedisuehli@env.ethz.ch

Towards online cloud tracking in convection-permitting COSMO simulations

Clouds occur on different spatial and temporal scales. Individual cloud systems show a large variability in terms of their lifetime; vertical and horizontal extent; and produced precipitation. Convection-permitting simulations allow, in principle, to study all types of clouds, including large-scale statocumuli, frontal cloud bands associated with warm conveyor belts, and convective clouds. However, the typical time resolution of model output, ranging from one to several hours, prevents a detailed investigation of cloud evolution and cloud tracks. In this project, we therefore aim to develop an online cloud tracking, which, in either two or three dimensions, identifies clouds at potentially every model time step and connects them meaningfully in time. Possible input variables in 2D and 3D, respectively, are vertically integrated total cloud water content and total cloud species. For identification in both 2D and 3D we make use of region-growing techniques to distinguish spatially connected clouds. One big challenge in this regard are large non-convective cloud structures. For tracking in time we mainly use area and volume overlap. We test these approaches first for short episodes of heavy precipitation in the Alpine region, starting offline (e.g. hourly output) and subsequently moving towards online-analysis. In addition to the shape and tracks of clouds, the algorithm also identifies key characteristics of the clouds, including vertical extent, hydrometeor content, and associated surface precipitation, as well as potential events of cloud mergings and splittings. On this poster, we will present the main elements of our approach and results from first applications within the crCLIM project.
Sakradzija, Mirjana

Max Planck Institute for Meteorology
mirjana.sakradzija@mpimet.mpg.de

Towards a parameterization of shallow cumuli across scales

Parameterization of shallow cumuli on the kilometer-scale grids in atmospheric models faces at least three major difficulties: (1) closure assumptions used in conventional parameterization schemes are not valid on these scales, (2) stochastic fluctuations become substantial and increase with horizontal grid resolution, and (3) convective circulations that develop on the kilometer-scale grids are under-resolved, grid-scale dependent and thus, they introduce artificial variability modes in the cloud fields. We present here an approach to parameterization that aims to addressing these three points. Fluctuations in a shallow cumuli ensemble are modeled in a scale-aware manner using a stochastic scheme for sub-sampling the convective ensemble distribution. This stochastic scheme is coupled to the Eddy-Diffusivity Mass-Flux (EDMF) parameterization in the ICON model to perturb the moist updraft area fraction, making the main closure assumption valid across scales. However, in a 3D numerical model an additional requirement is to reconsider the EDMF closure assumptions for the cloud layer vertical structure. Furthermore, the under-resolved grid-scale-dependent circulations increase the spatial variance and skewness of subgrid cloud properties compared to LES. So, we also discuss options for the cloud layer vertical structure parameterization and the effects of the convective gray-zone on the parameterization of cloud ensembles.
How well are observed stratocumulus to cumulus transitions reproduced in ECMWF short range forecasts?

Authors: Irina Sandu, Maike Ahlgrimm, Chris Bretherton and Jeremy McGibbon

The transition from unbroken stratocumulus to scattered cumulus clouds that occurs as boundary-layer air masses advect equatorward in the trades is one of the most prominent features of global cloud climatologies. Numerous studies based on conceptual models, observations and Large-Eddy Simulations focused on this transition and lead to a simple conceptual model explaining it. Yet, albeit our relatively good understanding of the processes underlying such transitions, reproducing them remains one of the most challenging tasks for global models. Here we use observations supplied by two recent field experiments to examine how well observed transitions between stratocumulus and shallow cumulus are reproduced in short range forecasts performed with the Integrated Forecast System of ECMWF. The two field experiments are: (i) the Cloud System Evolution in the Trades (CSET) airborne campaign which took place in July/August 2015 and which extensively sampled the stratocumulus to cumulus transitions through repeated sampling of the lowest 3 km of the atmosphere between California and Hawaii, including profiling, in-situ cloud and aerosol properties, turbulence, lidar and cloud radar; and (ii) the Marine ARM GPCI Investigation of Clouds (MAGICS) experiment which observed clouds along the North Pacific transect from Los Angeles to Hawaii using a regularly travelling container ship as the platform for surface, radiation and aerosol instrumentation, as well as a suite of active remote sensors and radiosonde launches. We will use the two data sets to understand the limitations of the current schemes that represent these type of clouds in the ECMWF model, at both current (approx. 16km) and future model resolution (approaching 8km at the Equator). An additional aspect we are particularly interested in is whether a global model at these resolutions can reproduce the mesoscale organisation in shallow convection that was observed in CSET, at least in short range forecasts.
Changes in convective mass flux, ice and liquid water paths, and tropical cyclone frequency due to global warming simulated by NICAM

Cloud feedback plays a key role in the future climate projection. Numerical experiments with the Nonhydrostatic Icosahedral Atmospheric Model (NICAM) for a present-day (CTL) and a future (GW) conditions show that high cloud fraction generally increases, opposed to many other CMIP3/5 models, while ice water paths (IWP) decreases. We estimate the contribution of tropical cyclones (TCs) to IWP and liquid water paths (LWP) associated with TCs and their changes between CTL and GW. The numerical results show that the TC-genesis of GW reduces to approximately 70% of CTL and the tropical averaged IWP and LWP are reduced. The contributions of IWP/LWP associated with TCs are analyzed with the radial distributions of IWP/LWP from the TC center at their mature stages and we find that they generally increase for more intense TCs. As the intense TC increases in GW, the IWP and LWP around the TC center of GW becomes larger than those of CTL. We further extend the above analysis to the convective mass flux to constrain the global frequency of TCs. The NICAM simulations showed that the reduction in the global frequency of TCs is much larger than that in the total tropical convective mass flux. Either a future increase in the frequency of stronger TCs or an areal increase in strong updrafts explains this difference. A reduction in the contribution of convective mass flux of TCs to total tropical convective mass flux also contributes to the difference. This study suggests that future intensification of TCs leads to future reduction in their frequency under the condition that the contribution of TC remains the same or smaller.
Savre, Julien

University of Cambridge

js2176@cam.ac.uk

High-resolution simulation of clouds and precipitation using hybrid finite-element methods

ATHAM-Fluidity is a new nonhydrostatic model recently developed for cloud-scale high-resolution atmospheric simulations. The dynamical core is based on a mixed finite-element discretization designed to operate on unstructured, adaptive meshes, making it a unique tool among existing atmospheric models. After careful evaluations using dry idealized atmospheric test cases (representative of atmospheric convection and gravity waves) for which the performances of the dynamical core and mesh adaptivity algorithm have been assessed, the model has been extended to handle moist atmospheric conditions and the presence of clouds. These new developments include the implementation of an active tracer concept to account for atmospheric moisture and hydrometeors, as well as a warm two-moment bulk microphysics scheme to parameterize the formation and evolution of liquid clouds and precipitation. First results obtained using ATHAM-Fluidity that show the formation and evolution of individual convective clouds will be presented. These simulations are performed under idealized atmospheric conditions but include the above mentioned warm microphysics scheme, a sub-grid scale parameterization for turbulence as well as appropriate boundary and large-scale forcings. Future works will include the implementation of more realistic land/ocean surface parameterizations as well as the inclusion of ice phase microphysics. ATHAM-Fluidity will ultimately be forced by meteorological data from observations or reanalysis to investigate actual cloud-scale weather events.
Schaefer, Sophia

*University of Reading*

s.a.k.schafer@pgr.reading.ac.uk

**Global importance of 3D cloud-radiation effects for radiative transfer and cloud development**

Interaction between clouds and radiation is crucial to both Earth’s energy balance and to cloud development. Complex 3D cloud shapes can have a significant effect on the interaction with radiation, but since radiation schemes in global weather and climate models only consider radiative transport in one vertical dimension, they cannot capture these effects. Because of the high computational cost of treating 3D cloud-radiation interaction in full, not much work has been done on investigating the importance of 3D effects on a global scale. We develop a new radiation model, the Speedy Algorithm for Radiative Transfer through Cloud Sides (SPARTACUS), which represents these effects in a computationally efficient way as transfer terms between clear and cloudy regions in a two-stream scheme. Using cloud radar observations, large eddy simulations and 3D Monte Carlo radiation calculations, we analyse the spatial distribution of radiative fluxes and heating rates within clouds, and the role played by cloud shape, size, inhomogeneity and organisation of clouds in a cloud field, and devise coherent parametrisations of these phenomena. Our modified scheme reproduces results in both longwave and shortwave from theory and full 3D calculations well and is much cheaper than 3D radiation schemes, allowing us to implement it globally in a modified version of ECMWF’s IFS radiation scheme. We find that 3D effects on cloud-radiation interaction are globally significant not only in the shortwave, but also in the longwave. Their local importance depends on the prevalent cloud type and cloud distribution. On a smaller scale, within each cloud, including 3D effects leads to significant changes in heating rates and thus a feedback on cloud development. We analyse the cloud changes caused by this feedback in the dynamical IFS model, globally and on local scales.
A fast forward operator for visible satellite images accounting for 3D effects

Satellite observations provide information on the cloud distribution and cloud properties in high spatial and temporal resolution and are thus well-suited for the verification of high-resolution NWP models and convective scale data assimilation. These applications require sufficiently fast and accurate forward operators. However, such operators exist so far only for thermal infrared and microwave radiance observations, which mainly provide temperature and humidity information. Observations in the visible and near-infrared spectral range contain complementary information about cloud properties like effective particle sizes, optical depths and water phase. Due to the importance of scattering, forward operators for the visible and near-infrared spectral range require complex radiative transfer methods and are computationally too expensive to be used in an operational context. To address this shortcoming, a fast forward operator for visible satellite observations has been implemented. The new 1D radiative transfer method used in the operator is based on a representation of the top of atmosphere reflectance as a fit function depending on the satellite viewing angles and six parameters describing the atmospheric state, the surface albedo and the sun position. For each parameter combination the coefficients of the fit function are determined by a least squares fit to results obtained with the discrete ordinate method (DISORT) and stored in tables. The computation of reflectances from the model state requires only linear interpolation in the coefficient tables and is thus several orders of magnitude faster than DISORT. The accuracy of the results relative to 3D Monte Carlo results is only slightly worse than for DISORT. To reduce the systematic errors of the operator further, the most important 3D effects are taken into account approximatively. Both cloud shadows and reflectance variations caused by the inclination of the cloud tops are considered.
Schemann, Vera

University of Cologne

schemann@meteo.uni-koeln.de

A budget analysis of variance of scalar variances in precipitating shallow cumulus convection

Vera Schemann (1,2) and Axel Seifert (3) 1: Max Planck Institute for Meteorology, Hamburg, Germany 2 Now: University of Cologne, Institute for Geophysics and Meteorology 3: Deutscher Wetterdienst, Offenbach, Germany

Shallow cumulus clouds cover large regions of the Earth's surface and are present on a large range of scales - from small cumulus clouds to large organized structures. Especially the development of precipitation is often accompanied by a change in spatial patterns or cloud organization. This effect drives the research and analysis presented in this study. To understand the connection between precipitation and the variability within a cloud field, the influence of microphysical processes on the evolution of scalar variances in shallow cumulus convection is investigated. Especially the total water variance budget is analyzed in detail, as the subgrid variability of this quantity is essential for the formulation of reasonable cloud process parameterizations. In this study a set of Large-Eddy-Simulations is used to calculate the budgets of the variance and vertical flux of total water as well as liquid water potential temperature. The driving question for the analysis is: how are the microphysical processes - accretion, autoconversion and evaporation of rain - influencing the evolution of these budgets? Which terms can be neglected and which would need to be parameterized in coarser models? Our analysis showed, that - while autoconversion and evaporation of rain can be neglected - accretion is a sink for the variances of total water and liquid water potential temperature. This reflects the process, that the formation of rain depletes the largest fluctuations in total water and with this decreases the variance. Following this result and the need to take this effect into account in coarser models, also a first simple parameterization for the accretion sink for the variance of total water is suggested, which could be applied for example in the framework of assumed PDF (Probability Density Function) cloud schemes.
Schlemmer, Linda

IAC ETH Zurich

linda.schlemmer@env.ethz.ch

Assessing Clausius-Clapeyron scaling of moist convection over land within an idealized convection-resolving modeling framework

Climate models suggest that climate change may imply an increase in heavy precipitation events, in some regions even despite reductions in mean precipitation amounts. The hydrological cycle is expected to undergo an intensification driven by the increase of the saturation vapor pressure with temperature of approximately 7%/K leading together with near-constant values of relative humidity to a non-linear increase of the specific humidity with temperature. Several studies indicate that hourly precipitation extremes can even exceed expectations from the Clausius-Clapeyron equation.

We study the processes leading to heavy precipitation events during episodes of mid-latitude diurnal convection over land with an idealized convection-resolving modeling framework. The framework allows to simulate diurnal convection in its equilibrium state, termed "diurnal equilibrium". We generate a wide range of convective states within this framework, covering changes in atmospheric temperature, lapse-rate and soil moisture content. The resulting response of the diurnal convection and associated cloud and precipitation development is then analyzed. As expected from water-vapor scaling we find an increase of heavy precipitation in accordance with Clausius-Clapeyron scaling for the case of homogeneous warming. For warmer atmospheres, the increasing water vapor content enhances cloud amount and precipitation. Moreover, clouds increasingly organize into larger clusters and become more efficient in converting the atmospheric water vapor into precipitation. However, if the warming is associated with a stabilization of the atmosphere, as is projected by many climate models, the highest percentiles of the precipitation distribution exceed Clausius-Clapeyron scaling. This can be explained by a shift to very localized, intense convective events. A decrease of soil moisture in contrast reduces precipitation amounts over all intensities and leads to the development of very localized precipitation patches.
Schmidli, Juerg

Goethe University Frankfurt

schmidli@iau.uni-frankfurt.de

Influence of the turbulence and convection parameterization on convective initiation in kilometer-scale simulations

The next generation of numerical weather prediction models will run with a grid spacing of about 1 kilometer. Deep convection is coarsely resolved at this grid spacing, but shallow clouds and boundary layer turbulence are too small to be resolved. Previous experience with NWP at MeteoSwiss and other institutions has shown significant biases at this resolution: shallow clouds tend to be underrepresented and a too sudden onset of deep convection occurs. We use idealized simulations to investigate the ability of a kilometer-scale NWP model (COSMO) to accurately represent the initiation and development of moist convection. In particular, we look into the role of boundary layer turbulence, horizontal mixing and the convection scheme. We do this by systematically exploring a number of case studies (GEWEX Cloud System Study (GCSS) cases as well as two previously documented cases of convection over topography), using both the kilometer-scale resolution setup and an LES setup with higher resolution. Using the latter setup as a reference, we aim to identify weaknesses and suggest improvements in the formulation of moist convection and turbulence. We look into the spatial distribution of turbulence, clouds and precipitation and use conditionally sampled statistics to investigate the properties of clouds and flow patterns. The standard convection scheme in COSMO captures the onset of clouds, but the liquid water content and mass-flux near cloud top are overestimated. This behavior can be improved with modifications in the closure, convective triggering and the entrainment-detrainment formulation. The kilometer-scale model performs surprisingly similar to LES simulations, even for phenomena which it only coarsely resolves, such as convective cold pools, slope flows and marginally resolved updrafts. We further discuss the effect of the horizontal mixing formulation and turbulence parameterization on the initiation and development of moist convection.
Schulz, Hauke

Max Planck Institute for Meteorology

hauke.schulz@mpimet.mpg.de

Observational quantification of the interaction between free tropospheric humidity and boundary layer structure

Studies of convective aggregation reveal a close relationship between the humidity and cloud structure in the lower troposphere and the rank column-integrated absolute humidity. Aggregation is thought to arise because of interactions between the dry and moist regions (as measured by the rank of the column measured humidity), driven in large part from the radiative impact of clouds in the dry atmosphere. The present study investigates these relationships using data, and thus complements more idealized studies based on model output. Five years of high-resolution long-term measurements from various instruments including a Raman lidar, with the capability of profiling water vapor through the troposphere, and a cloud radar collected at the Barbados Cloud Observatory serve as a starting point for the analysis. Due to the vicinity of the observatory to the equator, the annual shift of the Intertropical Convergence Zone makes it possible to encounter both subsiding and convective regimes at the site and enables in a first step a trans-regional reconstruction of vertical profiles of atmospheric humidity ordered by column integrated humidity, or moist static energy. This histogram gives some indication to what extent models represent the respective structure of the dry and convecting zones, especially in the driest regions where the radiative cooling is very sensitive to low clouds. The quantification of the cloud radiative effect as a function of the dryness of the atmosphere and the boundary layer structure can be extracted as additional knowledge from data. In a second step, findings will be evaluated and transferred to larger scales with additional airborne and satellite data sets.
Schween, Jan

*University of Cologne*

[jschween@uni-koeln.de](mailto:jschween@uni-koeln.de)

**Profiles of the Turbulent Humidity Flux: from measurement to water budget**

Advances in lidar technology allowed in the last years the development of robust Doppler lidars as well as Raman Lidars for profiling of the humidity content of the atmosphere above. Combining both kinds instruments should allow to calculate fluxes. We present data from the combination of a commercial available Doppler Lidar (HALO photonics, GB) and the University of BASILicata UV Raman lidar system (BASIL) research instrument. Following the principles of Reynolds averaging, the turbulent flux is the covariance between vertical wind speed and humidity. It is thus a statistical quantity describing the state of the atmosphere in a limited time interval. Several sources of uncertainty are investigated, starting from the inherent noise in lidar data, separation of the sensors (including a correction for this) and the limited sampling volume. Techniques commonly applied to surface data are used to estimate the optimal averaging length. The resulting fluxes are used for a budget estimate considering the turbulent flux at the surface, detrainment into the free troposphere at the top of the boundary layer and horizontal advection.
Seifert, Axel

DWD

axel.seifert@dwd.de

Modeling the melting of graupel and hail in a bulk microphysics parameterization

Authors: Vivek Sant and Axel Seifert

The melting rates of graupel and hail are decisive for the amount of ice reaching the ground, but the melting processes can also strongly affect the dynamics of convective and even frontal systems due to the associated cooling of the air. For comparison of high-resolution simulations with remote-sensing observations like radar an explicit prediction of the melting of graupel and hail allows for a more accurate treatment in the forward model, i.e. the calculation of radar reflectivities from model variables. To develop an advanced melting scheme the fundamental properties of melting graupel and hail are revisited and parameterizations are compiled based on available laboratory measurements of individual particles. Using those empirical relations in a spectral, i.e. size-resolved, 1D iceshaft model lays the foundation on which the new bulk model is derived. To this end, several simplifications are necessary. For example, we show that for a melting hail particle the internal conduction term, which in general depends on the actual temperature gradient between the engulfed ice core and the liquid surface, can be replaced by a simpler correction term considering only the thickness of the liquid layer. Shedding of melt water is a secondary process that occurs during melting and affects the fall velocity of the melting particle and also the melting rate itself. It is shown that a physically-based parameterization of shedding in a two-moment bulk scheme is possible, but large uncertainties remain due to the complexity of the microphysical behavior of melting graupel and hail. Based on this study, we suggest a new parameterization of the melting processes of graupel and hail for use in two-moment bulk schemes, which has the important advantage that the amount of liquid water on melting graupel and hail is explicitly predicted.
Seifert, Patric

TROPOS

seifert@tropos.de

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

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 \(-25^\circ\text{C}\) 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. Based on long-term observations of the Leipzig Aerosol and Cloud Remote Observations System (LACROS) (51°N, 12°E) the relationship between the temperature at the top of precipitation systems and the formed amount of precipitation was investigated. This allows to draw conclusions about the amount of precipitation formed by a certain ice nucleation mode. Second, it was investigated if regional differences in the heterogeneous ice formation efficiency lead to differences in the precipitation formation. To accomplish that goal, measurements of the instrument suite aboard the satellite GPM core observatory (Global Precipitation Measurement Mission) in regions around Leipzig (Germany, 51°N), Praia (Cape Verde, 15°N) und Punta Arenas (Chile, 53°S) were evaluated against the highly resolved measurements of the LACROS supersite at Leipzig. First results obtained from the LACROS dataset show, that only a fraction of approximately 1% of the total precipitation is formed via warm-rain processes (e.g., drizzle) without any ice nucleation involved. 40% of all precipitation is initialized solely via liquid-dependent ice nucleation, about 15% may involve deposition or condensation freezing in addition, whereas the remaining 45% are formed by any of the possible nucleation modes, including homogeneous freezing.
Seiki, Tatsuya

JAMSTEC
tseiki@jamstec.go.jp

Toward simulating thin cirrus clouds using a high resolution GCM

The distribution of simulated cirrus clouds over the tropics is affected by the particular model’s vertical grid spacing. To examine this effect, we use a high-resolution atmospheric general circulation model NICAM with 28-km and 14-km horizontal meshes. We show that a vertical grid spacing of at least 400 m is necessary to resolve the bulk structure of cirrus clouds. As one reduces the vertical grid spacing below about 1000 m, the visible cirrus cloud fraction decreases, the cloud thins (optically and geometrically), the cloud-top height lowers, and consequently, the OLR increases. These effects are stronger over the tropics. When using a vertical grid spacing of 400 m or less, the vertical profiles of effective radii and ice water content converge toward measurements (CloudSat satellite and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation).
Senf, Fabian

*TROPOS*

sentropos.de

**Meteosat-based Characterization of the Initiation and Growth of Severe Convective Storms over Central Europe**

The realistic representation of the transition between medium-size and deep convective clouds is one of the big challenges for state-of-the-art cloud resolving numerical models. To increase the scientific understanding of the convective growth process and also to support modelling activities, we present the investigation of the initiation and growth phase of severe convective storms over Central Europe for the years 2012 to 2014. Using data from the SEVIRI imaging radiometer aboard the geostationary Meteosat satellite, dynamical and microphysical properties of developing storms are collected and combined. Several satellite-based storm properties, e.g. cloud-top temperature, cloud-top cooling rate and cloud particle effective radius, are studied following storm tracks. In addition, onset and time rate of lightning, as well as changes in radar-based precipitation magnitude and heavy precipitation areas in vicinity of the storm tracks are considered. The time of maximum cloud-top cooling is considered for synchronization of the collected track properties. The majority of studied storms show a distinct maximum in cloud-top cooling rate. The cloud growth phase is divided into an initial updraft intensification period before the maximum cooling and a continued growth period afterwards. The initial updraft intensification period is more variable than the continued growth period and strongly depends on the initiation mechanisms. The two periods last around half an hour, making together around one hour of total satellite-derived convective growth. Connections between time rate of cloud-top cooling, anvil area changes, changes in top-cloud microphysical properties and precipitation strength are presented.
Sherwood, Steven

*University of New South Wales*

<s.sherwood@unsw.edu.au>

**Exploring emergent constraints on climate sensitivity**

Hope has been rekindled recently that we can infer Earth’s climate sensitivity from modern observations; this sensitivity includes not only the response of global temperature, but also of precipitation and its extremes, to global radiative forcings. To infer these from observations requires finding observable quantities or relationships in the natural variability or climatology that are governed by the same mechanisms that determine sensitivity to global forcings. Approaches based on local statistical relationships between temperature and another variable (cloudiness or rain) generally do not work because they are dominated by dynamical mechanisms different from those acting under global warming; as can be confirmed by testing them in models. I will show recent advances in two specific approaches that appear more promising: one based on the mechanism of Sherwood et al. 2014 which relates a measure of quasi-global lower-tropospheric mixing to cloud feedback, and another based on the use of fluctuations in global meteorological fields to infer forced responses via the fluctuation-dissipation theorem. In particular we find that high climate sensitivity and other patterns of behaviour commonly seen in high-sensitivity climate models, or their converse, can be reproduced by altering the behaviour of convective/mixing processes in the planetary boundary layer of a GCM. The former approach may therefore prove useful for understanding and quantifying global climate sensitivity, while the latter appears more promising for narrowing the range of regional precipitation responses.
Sourdeval, Odran

University of Leipzig

odran.sourdeval@uni-leipzig.de

Preliminary results of a new methodology for global ice crystal number concentration retrievals

Because of their crucial role on the Earth’s radiation budget, clouds are nowadays a concern of major importance for climate research. A myriad of retrieval methodologies have consequently been developed during the last decades in order to provide retrievals of cloud properties to the climate modeling community. Accurate products and climatologies of cloud properties such as the water content (CWC) or the number concentration of droplets (CDNC) or ice crystals (CINC) are indeed nowadays crucial for correctly parameterizing or validating the ice schemes used in recent climate models. While a large numbers of well-established methods are today dedicated to retrieving the CWC, very few of them provide operational CDNC retrievals and yet no CINC product exists from remote sensing measurements. This study presents a new space-borne product of CINC retrievals, based on the existing DARDAR (LiDAR/raDAR) methodology. The latter provides retrievals of ice cloud properties by retrieving parameters of an assumed particle size distribution, which can therefore be a posteriori used to infer a corresponding CINC. Preliminary results from this method are presented in this study, as global retrievals or as parameterizations as function of other metrics (e.g. temperature or ice water content). These results show coherent patterns in the global distribution of CINC, which are however difficult to validate due to the absence of other existing retrievals. As a validation attempt, DARDAR CINC retrievals are compared to existing parameterizations and to in situ observations from the recent SPARTICUS or ML-CIRRUS campaigns, which are believed to be less sensitive to the effect of ice crystal shattering on probes edges. Finally, this new product will be compared to the predictions of the two-moment ice scheme used in the HD(CP)2 high-resolution model for several golden days.
3D Water Vapor Measurements in the Boundary Layer with the UHOH Scanning Differential Absorption LIDAR

Florian Späth, Andreas Behrendt, Shravan Kumar Muppa, Simon Metzendorf, Andrea Riede, Volker Wulfmeyer
University of Hohenheim, Institute of Physics and Meteorology, 70599 Stuttgart, Germany

Water vapor distributions in the boundary layer and their variability and heterogeneities have been investigated with the scanning differential absorption lidar (DIAL) of University of Hohenheim (UHOH) in the HD(CP)2 Observational Prototype Experiment (HOPE) in western Germany in spring 2013 and in the Surface-Atmosphere-Boundary-Layer-Exchange (SABLE) campaign in south-western Germany in summer 2014. In this contribution, we will present different kinds of scanning water vapor DIAL measurements according to three different research topics. During HOPE, range-height-indicator (RHI) scans in two directions were performed to show the humidity heterogeneities within several kilometers and its impact on formation of clouds. During SABLE, with a plane-polar-indicator volume scan the 3-dimensional spatial structures of the boundary layer was observed for the first time. In this case, variations of the layer heights can be related to surface elevations. Low-elevation RHI scans close to the ground allow for measurements of the humidity gradient in the surface layer above different kinds of vegetation.
Spichtinger, Peter

*Johannes Gutenberg University Mainz*

[spichtin@uni-mainz.de](mailto:spichtin@uni-mainz.de)

**Subvisible cirrus clouds - investigations using a reduced order model**

In the extratropical and tropical tropopause region very thin cirrus clouds with optical depths smaller than 0.03 (so-called subvisible cirrus, SVC) occur very frequently. Although these clouds consist of very few ice crystals, they influence hydration and dehydration as well as the radiation budget. Thus, a physically correct representation of SVC in climate models is necessary. The formation of SVCs is not well known. It is generally assumed that heterogeneous nucleation (i.e. solid aerosol particles are involved) is the dominant formation mechanism for SVC, since the ice number concentrations are very low on the order of 10 per litre. However, there are some indications that also homogeneous freezing of aqueous solution droplets may play a role. Box model simulations indicate that at low vertical updrafts SVC may form via homogeneous nucleation. In order to investigate the importance of ice processes determining ice crystal concentrations for SVCs, we develop a reduced order model for this regime. From the standard bulk physics parameterisation we derive a set of three ordinary differential equations (ODEs) describing the main features of SVCs. We analyse the equations using mathematical methods from dynamical systems theory in order to determine the qualitative properties of the ODEs (e.g. attractors, limit cycles etc.) depending on environmental parameters. In fact, change in environmental parameters leads to a Hopf bifurcation, i.e. a qualitative change from an attractor system to a limit cycle. Additionally, we integrate the reduced order model for comparison. The results might be used for a simple but physically correct SVC model in large-scale models. Thus, this reduced order model strategy serves as a prototype for scalable cloud parameterisations.
Stein, Thorwald

*University of Reading*

t.h.m.stein@reading.ac.uk

**Observing the evolving characteristics of convective storms for model evaluation**

This presentation introduces the DYMECS project (Dynamical and Microphysical Evolution of Convective Storms), in which we have gathered a large database of over 1,000 3D storm structures on 40 convective days using an automated storm-tracking and scan-scheduling algorithm for the high-resolution Chilbolton radar in southern England. The 3D storm structures are used to statistically evaluate the 3D morphology of convective storms in the UK Met Office 1.5-km forecast model (UKV), as well as limited-area models nested inside the UKV at 500-m, 200-m, and 100-m grid length. Using single-Doppler retrievals of vertical velocity from profiling scans through storm convective cores, updraft widths and strengths are evaluated statistically. Our results clearly show the shortcomings of simulating convective storms in the UKV at 1.5-km grid length, as storm 3D structures are factors 2-3 too broad and updrafts are too wide yet weaker than observed, while the UKV also poorly represents the numerous short-lived storms of diameter smaller than 10 km. Simulations at 100-m and 200-m are comparable and produce adequate representations of convective storm structures and life cycles, though updrafts may be too narrow and the simulations tend to produce many intense but shallow storms, which are not observed. The results show the potential of high-resolution radar measurements in constraining models and informing their development. Furthermore, the real-time tracking of convective clouds and their updraught cores is shown to be essential for observing the evolution of convective storms.
Stengel, Martin

*DWD*

[link to email]

**Observing the glaciation process in clouds by tracking them with geostationary satellite observations**

The transition of clouds from liquid to ice phase is of crucial importance for the effect of clouds on climate because it significantly affects radiative properties, dynamics and the formation of precipitation. Observing the thermodynamic phase of clouds during their lifetime can help to understand these glaciation processes. The geostationary instrument SEVIRI onboard the MSG satellites provides unique opportunities to do this for individual clouds due its spatiotemporal imaging resolution, allowing the tracking of cloud objects, and due to its available spectral bands which allow for accurate retrievals of for example thermodynamic phase and cloud top temperature. In this presentation we will show results utilizing new SEVIRI-based, high-quality cloud-top retrievals of the Satellite Application Facility of Climate Monitoring. A tracking algorithm is applied to identify and follow all clouds that undergo the transition from liquid to ice phase while they develop. During this process important cloud variables such as cloud-top temperature are collected and analysed. Tracking clouds instead of global statistics will also allow a closer look at other circumstances that might impact the freezing such as the velocity of vertical motion. Similarities and differences of the inferred statistics to global (more sparsely sampled) polar-orbiting data will be analyzed. Authors: Martin Stengel (DWD), Corinna Hoose (KIT)
Stevens, Bjorn

Max Planck Institute for Meteorology

bjorn.stevens@mpimet.mpg.de

High Definition Clouds and Precipitation for advancing Climate Prediction: Large Eddy Simulation Study Over Germany

Author: Dipankar, Anurag

Understanding climate change requires understanding feedbacks due to clouds, which are leading source of uncertainty in the existing climate models. This uncertainty in the cloud fields in climate models are in turn due largely to the limitations of the shallow and deep convective parameterization. One expects to resolve convection on a grid of $O(100 \text{ m})$ resolution, thereby reducing the aforementioned uncertainty due to convective parameterization. In this resolution range, one can begin thinking of large-eddy simulation (LES) which has a sounder theoretical foundation for its subgrid-scale parameterization. Substantial initiatives have been taken internationally to approach this threshold of $O(100 \text{ m})$. For example, the Japanese group (Miura et al., 2007; Mirakawa et al., 2014) is approaching this threshold by doing global simulations, with (gradually) increasing grid resolution, to understand the effect of cloud-resolving scales on the general circulation. Our strategy, on the other hand, is to take a big leap forward by fixing the resolution at $O(100 \text{ m})$, and gradually increasing the domain size. We believe that breaking this threshold would greatly help in improving the parameterization schemes and reducing the uncertainty in climate predictions. To take this forward, the German Federal Ministry of Education and Research has initiated a project on High Definition Clouds and Precipitation for advancing Climate Prediction (HD(CP)2) that aims at limited area hindcast LES over Germany using the new unified modeling system ICON (Zängl et al., 2014, Dipankar et al. 2015). In this talk, we will present the numerical and technical details of the HD(CP)2 model and also present the results from our on-going efforts on LES over Germany. The simulation uses the nesting capabilities of ICON is used to gradually increase the resolution from the outermost domain, which is forced by the COSMO-DE data, to the innermost finest domain at $O(100 \text{ m})$. Furthermore, detailed analysis of the simulation results against the observation data will be presented.
Stier, Philip

University of Oxford

philip.stier@physics.ox.ac.uk

An integrated view of deep convection

Philip Stier, Sarah Taylor, Bethan White, Zak Kipling, Laurent Labbouz, Max Heikenfeld Department of Physics, University of Oxford, Parks Road, OX1 3PU, Oxford, UK

Atmospheric convection and its representation in climate models remains arguably one of the greatest uncertainties in our understanding and prediction of the climate system. In particular, the response of convective clouds to anthropogenic perturbations from greenhouse gas induced warming as well as to increases in aerosol remains poorly understood. Current evaluation strategies for convection parameterisations in climate models typically employ only a subset of the available observations and are often limited by the temporal sampling from sun-synchronous polar orbiting satellites. In this work we aim to deliver an integrated view of deep convection, providing stronger constraints on our understanding of convection and the representation in models. We focus on the Congo Basin characterised by high convective activity with limited spatial aggregation. We combine results from polar orbiting instruments, such as pdfs of cloud top heights from CALIOP and CloudSat, with the analysis of geostationary and time-resolved SEVIRI data to provide new insights into the morphology and diurnal cycle of convection. We use automated tracking of individual convective cells in SEVIRI data to investigate the convective lifecycle, from triggering to dissipation, and complementary data from MODIS to provide context about environmental conditions, such as aerosol optical depth. This synthesized view of deep convection is employed to evaluate and constrain convection and its response to environmental factors in high resolution WRF simulations as well as in the MPI Earth System Model in its standard configuration with a mass-flux based convection parameterisation and coupled to the Convective Cloud Field Model, an ensemble cumulus parameterisation with explicit microphysics.
Challenges in convection parametrisation

The demands on convection parametrisation have never been so wide – from the need to represent seasonal climate variability in global models, to assisting partially resolved representations within convection-permitting domains. But, coupled with real breakthroughs in the past few years that have cracked apart long-enduring biases in global models, this is an exciting time for convection modellers. What these developments reveal is that detailed physical understanding of convective processes, combined with innovative ways to provide simplified representations is the future of this area.

In this talk we will review the current state of the art in convection parametrisation, outline the remaining challenges, and look ahead to where we can hope to be in future years. In particular, I will give an overview of a new programme of research joint between UK universities and the Met Office over the next five years, with the united aim of significantly improving the representation of atmospheric convection across the entire spectrum of model scales.
Stratton, Rachel

Met Office

rachel.stratton@metoffice.gov.uk

A 4.5km convection permitting climate simulation over Africa.

As part of the IMPALA project to improve model processes for African Climate, the Met Office is performing two ten-year convection-permitting simulations at 4.5km over the entire African continent - a control run, and an equivalent climate-change run with increased CO2. The climate change simulations, when completed, will help provide better guidance on expected changes in extreme precipitation associated with convection. Previous work has shown that 4km convection permitting simulations can better resolve the diurnal cycle of convection, improve convection around coastal regions associated with sea breezes, respond better to variations in surface moisture, develop and propagate mesoscale scale convective systems and better couple to the large-scale flow, all problems common to many climate models running with convective parametrization. Here we present preliminary results from the control simulation, focussing on the scales over which the atmosphere is found to respond to convective activity.
Subramanian, Aneesh

*University of Oxford*

aneeshcs@gmail.com

**Stochastic Multi-scale Atmospheric Modeling: A route to improved forecasts for the Tropics**

Convection and cloud processes play a key role in the dynamics of the atmosphere, especially in the Tropics. Yet, even today our shortcomings in parameterising convection in global climate models (GCMs) are limiting our ability to simulate and understand the climate and weather of the planet. Recent innovative ideas on convection parameterisation such as super-parameterisation (embedding cloud resolving models within the GCM grid) or stochastic-parameterisation implemented in the ECMWF climate model has helped improve its representation of the climate and weather systems. These two approaches in convection parameterisation have emerged as new paths forward and complement the conventional approaches rather than replace them. We study the impact of these two approaches and a combination of the two on forecasts from weather to sub-seasonal timescales. Results from evaluation of forecast skill in the Tropics and for organized convective systems such as the MJO will be presented. We show that the combination of the two approaches improves reliability of forecasts, especially in regions that are mainly affected by deep convective systems. This has implications on improving conventional convection parameterisation using hybrid approaches as we await the exascale computing systems of the future to resolve convection in climate models. Aneesh Subramanian and T. N. Palmer (Department of Physics, University of Oxford)
Tao, Wei-Kuo

*NASA Goddard Space Flight Center*

[wei-kuo.tao-1@nasa.gov](mailto:wei-kuo.tao-1@nasa.gov)

### Uncertainty of Microphysics Schemes in CRMs

Cloud-resolving models (CRMs) with advanced microphysics schemes have been used to study the interaction between aerosol, cloud and precipitation processes at high resolution. But, there are still many uncertainties associated with these microphysics schemes. This has arisen, in part, from the fact microphysical processes cannot be measured (or observed) directly; instead, cloud properties, which can be measured, are and have been used to validate model results. A potential NASA satellite mission called the Cloud and Precipitation Processes Mission or CaPPM is currently being planned for submission to the NASA Earth Science Decadal Survey. This mission could provide the necessary global estimates of cloud and precipitation properties with which to evaluate and improve dynamical and microphysical parameterizations and the feedbacks between them in CRMs. In order to facilitate the development of this mission, CRM simulations have been conducted to identify those microphysical processes responsible for the greatest uncertainties in CRMs. In this talk, we will present results from three CRMs (NASA Unified-WRF, CSU RAMS and Goddard MMF). Specifically, we will conduct sensitivity tests to examine the uncertainty of the some of the key ice processes (i.e. riming, melting, freezing and shedding) in different microphysics schemes (Goddard 3ICE, 4ICE and RAMS) in these three models. The idea is to quantify how these different models' respond to changes of these key microphysics processes. Preliminary results indicate very similar model responses (surface rainfall and its intensity, anvil amount, LWP and IWP distribution) to changes of the riming process, thus suggesting that CRM simulations are particularly sensitive to riming independent of the modeling framework or the dynamical core.
Abstracts

Taylor, Sarah

University of Oxford

sarah.taylor@physics.ox.ac.uk

Observations of deep convective cloud lifecycles from SEVIRI

Convective clouds are a fundamental building block of tropical weather and climate. However, due to the complexity of convective processes and the wide range of relevant spatial and temporal scales, many basic convective processes remain poorly understood and convective lifecycles are not accurately simulated in global models. The effect of aerosols on convection is particularly controversial. Several potential interaction mechanisms have been suggested and correlations between satellite retrievals of aerosol and cloud properties observed. However, recent studies suggest a significant proportion of this correlation may be due to meteorological co-variation. In this study we use satellite observations from the geostationary SEVIRI instrument to quantify convective cloud lifecycles and investigate interactions between convection, aerosols and meteorology. SEVIRI provides continuous, high time-resolution observations over a large area. Unlike low earth orbit satellites, SEVIRI is therefore able to sample the entire lifecycle of individual clouds. SEVIRI also covers the Congo Basin, one of the most convectively active regions on the planet and source of some of the largest global emissions of biomass burning aerosol. We combine SEVIRI observations with the Cumulonimbus Tracking and Monitoring (Cb-TRAM) algorithm to identify and track individual convective clouds in the Congo Basin. Our study is divided into two periods, corresponding to peak rainy and biomass-burning seasons. Tracked clouds are collocated with aerosol and cloud properties from SEVIRI and with precipitation and vertical cloud structure retrievals from TRMM and CALIPSO. Tracked clouds and collocated variables are rotated onto a common direction of motion, creating composite images of clouds at various stages of development. Composites are used to quantify variability in their horizontal and vertical structure. By clustering composites according to their meteorological environment, we are also able to take advantage of SEVIRI’s high time-resolution observations, to investigate the contribution of meteorology to observed correlations in aerosol and cloud retrievals.
Testorp, Sören

*Free University Berlin*

testos@zedat.fu-berlin.de

**Preparing for OLCI Cloud Top Height Retrieval**

Cloud top height retrievals, with the O2 A-band method, with passive imaging spectrometers as MERIS and the upcoming OLCI are sensitive towards the assumed vertical profile of cloud extinction. The spectral measurements of those passive instruments are limited in their characterization of the vertical structure of clouds. In preparation for the upcoming Ocean Land Colour Instrument (OLCI) on-board ESA’s Sentinel-3 satellite we introduce a procedure to estimate the vertical profile of cloud extinction through a cloud classification by spatial heterogeneity. Based on the grey level co-occurrence matrix (glcm) textural parameters are retrieved for each pixel. A random forest classifier uses the texture measures as basis to assign a cloud class for each individual pixel. For each cloud class an average vertical extinction profile is retrieved from CloudSat CPR measurements. The procedure is tested with MODIS Aqua Level 1B calibrated radiances for bands 1, 17 and 32. For our cloud top height retrieval with OLCI the O2-A band method will be applied, which is based on the ratio of measured radiance in an absorption channel and a window channel. In contrast to MERIS, OLCI has multiple channels within the O2-A absorption band. Therefore, sensitivity studies are performed in order to deduce the available additional information about the cloud.
Thompson, Gregory

NCAR
gthompsn@ucar.edu

Towards improving the representation of high-resolution cloud forecasts through the direct coupling of microphysics and radiation parameterizations in the WRF model

Each Spring, numerous convection-permitting ensemble forecast models are run daily by Oklahoma University's Center for Analysis and Prediction of Storms (OU-CAPS) to support severe weather operations in the U.S. The ensemble model framework facilitates various physics and initial/boundary data members for detailed sensitivity studies and potential parameterization improvement efforts. One recent study found that the Weather Research and Forecasting (WRF) model predicted less overall clouds than was observed, particularly in the mid-troposphere, but that properly connecting the assumptions of particle sizes in the microphysics scheme to the radiation scheme resulted in sensible cloud-radiation indirect effects and modest improvements in simulated IR brightness temperature, amount of solar radiation reaching the ground, and surface temperature. The combined approach of evaluating all three types of observations revealed the root model biases better than evaluating any single variable, which could have otherwise led to drawing improper conclusions about improving the physical parameterizations. Additional research now focuses more specifically on the under-prediction of mid-tropospheric clouds, even at moderately high resolution with grid spacings of approximately 4 km.
Tompkins, Adrian

ICTP
tompkins@ictp.it

Organization of tropical deep convection in low vertical wind shears: The role of boundary conditions and model diffusion

Understanding of the role of deep moist convection in the tropical climate has been previously advanced by conducting idealized simulations of radiative-convective equilibrium. These often showed spontaneous organization of the convection, variously attributed the physical mechanisms involving water vapour, cold pool (thermo)dynamics and radiative-feedbacks. Using convection “permitting” simulations with a typically employed 2km horizontal resolution, we first show that both the occurrence and strength of organization is dependent on subgrid-scale diffusion assumptions employed and how the mechanism for this involves water vapour entrainment into convective updraughts. We then demonstrate how the organization state is sensitive to the experiment boundary conditions employed. Negative feedbacks involving the lower boundary surface temperature that are often neglected in radiative-convective equilibrium simulations may act to prevent convective organization.
Tompkins, Adrian

ICTP
tompkins@ictp.it

Generalizing Cloud Overlap Treatment to Include the Effect of Wind Shear

Six months of CloudSat and CALIPSO observations have been divided into over 8 million cloud scenes and collocated with ECMWF wind analyses to identify an empirical relationship between cloud overlap and wind shear for use in atmospheric models. For vertically continuous cloudy layers, cloud decorrelates from maximum toward random overlap as the layer separation distance increases, and the authors demonstrate a systematic impact of wind shear on the resulting decorrelation length scale. As expected, cloud decorrelates over smaller distances as wind shear increases. A simple, empirical linear fit parameterization is suggested that is straightforward to add to existing radiation schemes, although it is shown that the parameters are quite sensitive to the processing details of the cloud mask data and also to the fitting method used. The wind shear–overlap dependency is implemented in the radiation scheme of the ECMWF Integrated Forecast System. It has a similar-magnitude impact on the radiative budget as that of switching from a fixed decorrelation length scale to the latitude-dependent length scale presently used in the operational model, altering the zonal-mean, top-of-atmosphere, equator-to-midlatitude gradient of shortwave radiation by approximately 2 W m\(^{-2}\).
Tornow, Florian

*Free University Berlin*

florian.tornow@fu-berlin.de

**Understanding multi-view broad-band radiance co-registration: exploitation of micro-physical cloud parameters**

In order to constrain climate predictions with a radiation budget, reliable estimates on outgoing top-of-atmosphere (TOA) long- and shortwave (LW and SW) fluxes are necessary. These estimates are based on broad-band radiances as well as information on atmospheric and surface properties. The Earth Clouds, Aerosols and Radiation Explorer (EarthCARE) mission, to be launched in 2018, will be equipped with a multi-view broad-band radiometer (BBR), allowing to observe one scene from a forward, nadir and backward viewing angle. For the common observation, we, previously, used existing and developed new radiance co-registration methods. These methods respond to the large-scale (O[100km²]) 2D (i.e. highest reflecting layer) or 3D structure of clouds. In this study, we focus on the responses of radiance co-registration together with their underlying micro-physical cloud properties. Ultimately, we aim at a better understanding of which micro-physical properties drive co-registration attributes, connected to cloud’s large-scale structure. For that, we took model output from the High Resolution Deterministic Prediction System (HRDPS) and a 3D Monte-Carlo Radiative Transfer Model (3D-MC RTM), simulating TOA radiances under EarthCARE-BBR-like conditions. Extracting respective information on clouds and radiance co-registration, we, finally, identified micro-physical cloud parameter, which responded to different co-registration attributes.
Multi-sensor characterization of mammatus clouds in Europe and the U.S.

The microphysics and generation mechanisms of mammatus clouds are still not completely understood. For the first time multi-sensor observations of mammatus clouds are analyzed in order to gain a more detailed description of their spatio-temporal distribution and microphysical characterization. Remarkably strong and pronounced polarimetric radar signatures are detected in Europe and the U.S.A along the sloping bases of respective thunderstorm anvils with mammatus. Horizontal reflectivity \( Z_H \) decreases and differential reflectivity \( Z_{DR} \) rapidly increases towards the bottom of the anvil signaling differential sedimentation of liquid drops at very low subfreezing temperatures. For an exceptional supercell observed in Germany on June 6, 2014, (Pentecost event) \( Z_{DR} \) exceeds 2 dB for mammatus clouds in the leading anvil, hinting to large raindrops of diameters up to 4 mm at the very bottom of sloping anvils. \( Z_{DR} \) observed in Oklahoma, U.S.A, thunderstorm anvils even exceed 4 dB which means that largest raindrops have diameters up to 5 - 6 mm at the very bottom of sloping anvils. Supplementary monitoring of the mammatus clouds observed during the Pentecost event with a 35.5GHz cloud radar confirm a wide spectrum of liquid drops generated at the base of the anvil, even at temperatures between -15°C and -30°C corresponding to 6km and 8km heights, respectively. These drops surely coexist with ice particles but their amount seems insufficient to deplete the liquid water generated in the very localized and strong updrafts with magnitudes up to 1.5m/s. A mammatus detection strategy based on precipitation radar data is presented, which has been used so far mainly for the detection of updrafts in precipitation systems, but allows for area-wide monitoring of mammatus. The detection strategy introduced is also relevant for aviation security due to the presence of enhanced turbulence and supercooled liquid in the mammatus region.
Lidar-derived Insights into Convective Boundary Layer Turbulent Structure

Lidars are able to measure profiles of water vapor, temperature, vertical winds, and aerosol backscatter at high temporal and spatial resolution. These observations are analyzed to provide profiles of 2nd and 3rd order moments that characterize the turbulent motion in the convective boundary layer (CBL). An analysis of water vapor mixing ratio observations from an operational Raman lidar over 300 CBL cases at the mid-latitude continental ARM Southern Great Plains site demonstrates high correlation between the gradient of the water vapor at and the variance in the water vapor the top of the CBL (i.e., at zi). The skewness of the water vapor distribution has a repeatable change of sign from negative to positive values at 0.95 zi. Furthermore, the variance at the top of the CBL can be used to predict the shape of the 3rd order moment of water vapor throughout the upper portion of the CBL. A separate analysis of aerosol backscatter from 17 cases observed by a high spectral resolution lidar (HSRL) about 100 km south of the ARM site also shows that the change in the skewness changes from negative to positive at 0.95 zi. Furthermore, due to the very low random noise level in the HSRL, a well-defined relationship between the skewness and kurtosis of the backscatter signal is seen between 0.85 zi and 1.05 zi. The relationships observed by these lidars over many cases that span a range of environmental conditions provide a unique dataset that is being used to evaluate the structure of turbulence produced by large eddy simulation (LES) and other models.
Unterstrasser, Simon

DLR

simon.unterstrasser@dlr.de

The Lagrangian ice microphysics code LCM within the LES model EULAG: basic overview and selected application examples

The Lagrangian Cirrus Module (LCM) is a Lagrangian ice microphysics code that is fully coupled to the LES model EULAG. The ice phase is described by a large number of simulation particles (order O(1e6) - O(1e9)) which act as surrogates for the real ice crystals. The simulation particles (SIPs) are advected and microphysical processes like deposition/sublimation and sedimentation are solved for each individual SIP. More specifically, LCM tracks ice nucleation, growth, sedimentation, aggregation, latent heat release, radiative impact on crystal growth, and turbulent dispersion. The aerosol module comprises an explicit representation of size-resolved non-equilibrium aerosol microphysical processes for supercooled solution droplets and insoluble ice nuclei. First, an introduction to LCM is given focusing on the implementation of a Lagrangian model within the grid-based EULAG framework. Second, application examples of LCM like simulations of contrail-cirrus and natural cirrus and their competition are presented.
van Laar, Thirza

University of Cologne

vanlaar@meteo.uni-koeln.de

Towards realistic cumulus cloud resolving simulations at supersites

Realistic fine-scale shallow cumulus cloud resolving simulations are performed to improve our understanding of the interactions between surface heterogeneity and boundary-layer cloud fields. For this purpose we apply the ICON (ICOsahedral Non-hydrostatic) model on a regional domain. ICON has been partly developed by the ongoing project HD(CP)2 (High Definition Clouds and Precipitation for Climate Prediction), which has the aim of getting a better grip on cloud and precipitation processes and their implication for climate prediction. The model domain is centred around JOYCE, an observational supersite in Jülich (Germany). To optimize the realism of the simulation, use is made of heterogeneous surface forcings and non-periodic boundary conditions. A number of prototype cumulus days is simulated, the results of which are evaluated against observations. The focus lies on bulk cloud properties and the vertical structure of the boundary layer. The ICON results are intercompared with available idealized LES results. Sensitivity of the results to the model set-up (e.g. resolution) is assessed.
van Stratum, Bart J.H.

Max Planck Institute for Meteorology

bart.vanstratum@mpimet.mpg.de

The influence of misrepresenting the nocturnal boundary layer in low-resolution large-eddy simulation on daytime convection

The influence of poorly representing turbulent and thermodynamic processes in the nocturnal boundary layer (NBL) on the following day of convection is studied using both observational data and large-eddy simulation (LES). The first part of this study focusses on (turbulent) mixing processes. Guided by observational data from Cabauw (Netherlands) and Hamburg (Germany), the typical summertime nocturnal conditions are characterized and used to design idealized numerical experiments of the diel cycle of convection. A sensitivity study on resolution is performed with the UCLA-LES code, with grid spacings ranging from $\Delta=3.125$ m — in which most nocturnal turbulence is resolved — to $\Delta=100$ m — which is clearly insufficient to resolve the NBL. Although the low-resolution experiments produce substantial biases at night, the influence on the following day of convection is shown to be small. The second part of this study focusses on the influence of the nocturnal biases on the formation of low clouds or fog. Using both observational data (Cabauw, Hamburg and Karlsruhe) and an idealized conceptual framework (with a realistic representation of the vertical structure of the NBL), the conditions leading to saturation are explored. The results indicate that model biases might prevent the formation of shallow and optically thin layers of fog, but apart from that no significant biases in fog or low clouds are to be expected.
van Weverberg, Kwinten

Met Office

kwinten.vanweverberg@metoffice.gov.uk

Using ARM-data to constrain the critical relative humidity in a large-scale cloud model

The representation of sub-grid cloudiness variability in NWP and climate models remains important, even at convection-permitting grid spacing of a few kilometres. The parametrisation of this variability usually revolves around defining a ‘critical relative humidity’ (RHcrit). This is the grid-box mean relative humidity, at which part of the grid box is assumed to be saturated (and hence clouds start to appear). With the advent of seamless models, applied over a range of resolutions, the common approach of applying a time- and space invariant vertical profile of RHcrit becomes increasingly problematic. To constrain the value of RHcrit, detailed observations of the (co-)variance of temperature are moisture are needed. In this study, two years of continuous very high temporal resolution lidar, radar and sounding measurements at the U.S. Department of Energy Southern Great Plains (SGP) Central Facility were used to study the temporal variability of RHcrit. To remove noise from the lidar data, the autocovariance filtering technique described by Lenschow et al. (2000) and Turner et al. (2014) was applied. It is shown that RHcrit at the SGP exhibits a very distinct diurnal cycle and is typically lowest near the boundary layer top around noon. Furthermore, RHcrit can be reasonably well predicted from a combination of the surface sensible heat flux, wind shear near the boundary layer top, the dry static energy within the boundary layer and the assumed grid box volume. Observed values of RHcrit were compared against a recently developed RHcrit parametrisation, based on the simulated turbulent mixing in the boundary layer. For a six week simulation at the SGP, it was found that this parametrisation produces reasonable values of RHcrit during daytime, but tends to underestimate RHcrit at night. Possible reasons for this nocturnal underestimation of RHcrit and consequences for forecasts of low clouds will be discussed.
Vogel, Raphaela

*Max Planck Institute for Meteorology*

raphaela.vogel@mpimet.mpg.de

**The role of precipitation and organization in the response of shallow trade-wind clouds to warming**

Using highly resolved large-eddy simulations over a range of domain sizes, we investigate the influence of precipitation and convective organization on the thermodynamic structure of the trade-wind boundary layer, and elaborate how this modulates the warming response. Understanding the influence of precipitation and organization is important for understanding the energetics of the trades as a whole, and thus its interaction with the inner tropics. By providing an additional heating and drying in the inversion layer, precipitation arrests the deepening of the boundary layer. From reevaporating precipitation and compensating heating of convection and subsidence, a moister and warmer boundary layer develops. This influences the response of shallow convection to a 4 K uniform warming at constant relative humidity, as it efficiently buffers the boundary layer against deepening and relative drying. Whereas changes in the vertical distribution of cloud fraction near cloud tops can be substantial, total cloud cover and albedo decrease only slightly with warming in all cases considered; demonstrating the robustness of marine boundary layer cumuli—in particular their near base cloud fraction—to changes in the large-scale forcing. The sensitivity to the presence of deep aggregated clouds nearby, however, is strong. The formation of a few deep clouds results in a shallower, warmer and drier boundary layer with reduced cloud cover. The formation of these deep clouds only occurs on a sufficiently large domain (∼50x50 km^2), is yet independent of whether convection precipitates or not, raising the question if cold pool dynamics created by precipitation are a necessary factor for shallow convection to aggregate into larger and deeper clusters.
Abstracts

Vogelmann, Andrew

Brookhaven National Laboratory

vogelmann@bnl.gov

Routine Large-Eddy Simulations of Continental Shallow Convection – Workflow Development

The U.S. Department of Energy’s Atmospheric Radiation Measurement (ARM) Climate Research Facility is developing the capability to routinely perform large-eddy simulation (LES) modeling at its permanent sites. The effort, called the LES ARM Symbiotic Simulation and Observation (LASSO) Workflow, is being designed to complement the extensive megasite observations with LES output to support the study of atmospheric processes and support the improvement of the parameterization of these processes in climate models. Megasite observations are used to constrain large-eddy simulations to provide a complete spatial and temporal coverage of observables and also provide information on processes that cannot be observed. The focus is initially on continental shallow convection at the ARM megasite in Oklahoma, USA, with a plan to expand the modeling to include other meteorological conditions and sites once the methodology has been established. This presentation describes initial results from the ensemble forcing methodology, evaluation of the ensembles using ARM observations, and the combination of LES output with observations for the construction of multi-dimensional and dynamically consistent “data cubes,” which are aimed at providing the best description of the atmospheric state for use in analyses by the community.
New particle formation due to enhanced radiation around trade wind cumuli near Barbados

A few studies from the 1990s show the occurrence of new particle formation in connection with clouds for individual cases. Recently, the focus of aerosol/cloud research went more to the direction of activation of CCN to cloud droplets. However, the other way might be interesting too: How does the cloud influence the aerosol population in its environment? During CARRIBA (Cloud, Aerosol, Radiation, and Turbulence in the trade wind regime over Barbados) 2010/2011 helicopter-borne measurements of meteorological, aerosol, and cloud parameters with high spatial resolution in the cloud layer around Barbados have been performed. During these flights 91 cases of new particle formation (NPF) in the vicinity of clouds have been observed and were analysed. Obviously, most events were related to an enhanced irradiance in the cloud region and were characterized by sharp gradients. The mean length of the events was 100 m, which is hard to resolve with research aircraft due to their higher true air speed. An estimate of the lifetime of the burst for one case study results in 140 s. That means aerosol particles were formed and grew into detectable sizes (< 7 nm) within this time. The frequent observation of NPF near clouds leads to the conclusion that clouds edges provide a favourable environment due the enhanced radiation for the production of precursor gases and enhanced turbulence to provide the required super saturation of precursors. Thus marine cumulus clouds do not only play an important role as particle sinks due to activation and the following effects on the radiation budget but also as a source for aerosol particles.
Weijenborg, Chris

Meteorological Institute
cwborg@uni-bonn.de

Potential Vorticity anomalies associated with deep moist convection

Severe weather extremes like extreme rainfall are often not well covered by numerical weather prediction models. The WEX-MOP (Mesoscale weather extremes: Theory, spatial modeling and prediction) project aims at improving the forecast of those extremes, using data of the non-hydrostatic COSMO-DE. Potential vorticity (PV) received not much attention on the convective weather scale. PV is tied to the balanced structure of the flow and has been useful in describing synoptic scale processes like cyclogenesis. Deep moist convection is per definition unstable, and therefore balance is not directly expected on the convective weather scale. We hypothesize that PV anomalies on the convective weather scale might still be “quasi-balanced”. Moreover, even when PV is not conserved, PV might still be useful to indicate the importance of diabatic processes. To test our hypothesis we created a climatology of PV dipoles associated with storm cells. To accomplish this, we use a tracking algorithm applied to maxima of the vertical velocity during 9 severe weather cases in COSMO-DE. Composites show that even when averaging over 3165 storm cells a clear PV dipole pattern is visible. This is consistent with theory and with related structures in the mass and momentum fields and could be termed a statistical balance. Intense convective cells, measured by e.g. precipitation rates, show a monopole “supercell” structure. We also discuss the possible use of PV as a predictor of severe weather.
Weisheimer, Antje

University of Oxford & ECMWF

antje.weisheimer@physics.ox.ac.uk

The impact of stochastic physical tendency perturbations on tropical convection in seasonal forecasts with the coupled ECMWF system

In order to explicitly represent uncertainties in physical parametrisation schemes, ECMWF’s seamless ensemble forecasting system from days to months ahead applies stochastic multiplicative perturbations to the physical tendencies of temperature, wind and humidity (SPPT scheme). In a set of seasonal re-forecast experiments over a 30-year period the impact of these model perturbations on the model climatology and its forecast quality is analysed. It is found that the stochastic SPPT scheme leads to a reduction of the overly active deep convection in the tropics with reduced OLR, clouds, precipitation and wind biases. It also helps to increase the frequency of MJO events in all 8 phases although the model still is not capable to simulate enough MJO events. Positive impacts on more reliable El Nino forecasts were also found.
Weismüller, Maren

University of Cologne

mweis@meteo.uni-koeln.de

Exploring a plume-based mass-flux scheme in the boundary-layer gray zone

We investigate the behavior of plume-based mass flux parameterizations in the gray zone of boundary layer convection, to inform the development of scale-aware and scale-adaptive parameterizations. To this end, the Eddy diffusivity Mass flux scheme with multiple plumes, named ED(MF)^n, is implemented in a Large-Eddy Simulation (LES) model. This way, the LES is used as a non-hydrostatic larger-scale model, providing a convenient platform for investigating the behavior of parameterizations across the boundary-layer gray zone. First, as a feasibility study, a single plume is launched in every column of the LES in an offline, diagnostic way, without affecting the simulation. We find that the plumes are sensitive to the LES columns in which they rise, feeling the presence of LES clouds. A plume budget analysis shows that the plume termination height is mostly determined by the mixing term, and not so much by the buoyancy term. Then, the ED(MF)^n is made interactive with the resolved flow, replacing the LES-subgrid scheme. The work performed by the scheme reduces with increasing LES resolution, due to the size-filtering applied in the ED(MF)^n framework. An encouraging result is that the total specific humidity flux is conserved across the investigated range of LES resolutions, covering the gray zone between 10m (large-eddy resolving) and 10km (regional-scale). The sensitivity of the results to various model parameters is assessed.
Wernli, Heini

ETH Zurich

heini.wernli@env.ethz.ch

Warm conveyor belts - important cloud systems in the extratropical storm track regions

Warm conveyor belts (WCBs) are coherent moist airstreams in extratropical cyclones that ascend from the (oceanic) boundary layer to the upper troposphere. During the ascent of typically more than 600 hPa within 1-2 days, clouds form and large amounts of latent heat are released. From a weather perspective WCBs are important because they contribute to many extreme precipitation events and because they have the potential to strongly modify Rossby waves and instigate atmospheric blocking. From a climate perspective one of their key aspects is the complex cloud evolution, which involves warm clouds at low levels, mixed-phase clouds in the mid-troposphere and ice clouds in the upper-tropospheric outflow regions. In some WCBs embedded convection may play an important role. This presentation will show that: (i) WCBs are frequent flow features of the extratropical storm tracks, (ii) WCBs are involved in many extreme precipitation events, (iii) WCBs are associated with high values of midlatitude ice water content and lead to a strong radiative cloud forcing, and (iv) significant model uncertainty exists for the mixed-phase cloud period of WCBs and the treatment of embedded convection. Convection-permitting simulations and the upcoming field experiment NAWDEX will be essential for better constraining these key processes influencing extratropical storm track dynamics.
Convective response to aerosol perturbations in high-resolution simulations is highly sensitive to the microphysics representation.

Aerosols, acting as cloud condensation nuclei (CCN), affect deep convection through their influence on cloud and precipitation microphysics over a wide range of spatiotemporal scales. Recent theoretical and modelling studies have indicated that aerosol-induced precipitation suppression in the warm phase may lead to the invigoration of deep convection. However, observational evidence has yet to confirm this hypothesis outside of factors such as synoptic covariability, retrieval errors and sampling artefacts, all of which may dominate the observed relationship between satellite-retrieved aerosol and cloud properties. Moreover, the modelling systems used in such studies rarely account for processes that may buffer the cloud and precipitation response to aerosol perturbations. In this study we investigate the sensitivity of the aerosol perturbation response to different degrees of sophistication in the representation of aerosol-cloud processes. High-resolution convection-permitting simulations are performed with the WRF model first using a two-moment bulk microphysics representation with prescribed cloud droplet number concentration (CDNC) and then using spectral bin microphysics with a prescribed initial CCN profile (Khain et al., 2011, Iguchi et al., 2012). In this setup, CCN activation is described using Koehler theory, but aerosol-cloud feedback processes such as wet scavenging remain unaccounted for. We then couple the WRF spectral bin microphysics to a simple CCN recycling scheme, which allows a more sophisticated representation of aerosol-cloud interactions without the expense of full coupled chemistry. We show that the cloud and precipitation response to aerosol perturbations is highly sensitive to the aerosol-cloud microphysics description. These results have significant implications for future modelling studies of aerosol-convection interactions.
Convection and its upscale effects in the Indian Monsoon: Insights from convection-permitting multi-day simulations over Indian Subcontinent

Met Office Unified Model (UM) climate simulations, like many global models, show large errors in rainfall for the Indian Summer Monsoon, with a wet bias over the equatorial Indian Ocean, and a dry bias over India. Here we use the first multi-day continental-scale UM simulations, with grid-spacings that allow explicit convection, to examine how convective parametrisation contributes to the growth of these biases. We focus on the diurnal cycle of convective cloud and precipitation and how this interacts with the larger scale circulation and transport of moisture. UM simulations for a 21 day period (21 Aug to 9 Sep 2011), with an overlap in grid-spacing between convection-permitting (12, 8, 4 and 2.2 km) and parametrised (120, 24, 12 and 8 km) runs, are analysed. The explicit simulations have a greatly improved diurnal cycle of rainfall over India, but peak 1-2 hours earlier than observed. The parametrised runs peak 4-5 hours early, a problem common to many global models. The delay in convective rainfall and cloud in the explicit runs allows greater surface insolation and generates a greater land-sea temperature contrast, enhancing onshore flow of moist air. Greater rainfall in explicit runs corresponds to greater latent heating of the atmosphere (with a magnitude that dominates the differences in radiative heating). This generates a deeper monsoon trough in explicit runs, again favouring transport of water vapour into the continent. These differences are found to be a function of convection, not model timestep. Model differences are shown to evolve significantly through the 21-day period, in particular with the arrival of a low pressure system over India from the Bay of Bengal on 29 Aug. The contribution of this to the differences in mean state are discussed.
Wing, Allison

Lamont-Doherty Earth Obs., Columbia U.

awing@ldeo.columbia.edu

Role of radiative-convective feedbacks in tropical cyclogenesis in rotating radiative-convective equilibrium simulations

"Self-aggregation" is a mode of convective organization found in idealized numerical simulations, in which there is a spontaneous transition from randomly distributed to organized convection despite homogeneous boundary conditions. Self-aggregation has primarily been studied in a non-rotating framework, but it has been hypothesized to be important to tropical cyclogenesis. In numerical simulations of tropical cyclones, a broad vortex or saturated column is often used to initialize the circulation. Here, we instead allow a circulation to develop spontaneously from a homogeneous environment in 3-d cloud-resolving simulations of radiative-convective equilibrium (RCE) in a rotating framework, with interactive radiation and surface fluxes and fixed sea surface temperature. The goals of this study are two-fold: to study tropical cyclogenesis in an unperturbed environment free from the influence of a prescribed initial vortex or external disturbances, and to compare cyclogenesis to non-rotating self-aggregation. We quantify the feedbacks leading to tropical cyclogenesis using a variance budget equation for the vertically integrated frozen moist static energy. In the initial development of a broad circulation, the feedback processes are similar to the initial phase of non-rotating aggregation. Sensitivity tests in which the degree of interactive radiation is modified are also performed to determine the extent to which the radiative feedbacks that are essential to non-rotating self-aggregation are important for tropical cyclogenesis. Finally, we examine the evolution of the rotational and divergent flow, to determine the point at which rotation becomes important and the cyclogenesis process begins to differ from non-rotating aggregation.
Parameterizing subgrid-scale hydrometeor transport in deep convection

To improve representations of convection in GCMs and to enable them to account for the impact of aerosols on all type of clouds, a growing number of convection parameterizations are being augmented with microphysical representations of cloud and precipitation. Because neither convective updrafts nor spatial cloud structure are explicitly resolved by these schemes, the convective (subgrid-scale) vertical transport of hydrometeors needs to be parameterized. Recently, Wong et al. (2015) proposed a scheme that bivariate conditionally samples joint (2D) distributions of vertical velocity and hydrometeor mass mixing ratios into quadrants. Scaling is then applied to quadrant mean fluxes to account for within-quadrant correlations between vertical velocity and the microphysics. Their diagnostic evaluation showed that the scheme was able to reproduce the vertical hydrometeor fluxes from their high-resolution benchmark simulation well. Typically, however, the joint distributions are unknown and need to be parameterized. Here, we extend the proposed scheme for use in an assumed probability density function (PDF) scheme when only marginal (1D) PDFs of vertical velocity and hydrometeor mixing ratios are available. The parameterization is developed using high-resolution simulations of continental and tropical deep convection. The 3D cloud-resolving model used for guidance has a horizontal grid spacing of 250 m and employs the Morrison microphysics scheme, which treats prognostically mass and number mixing ratios for four hydrometeor types (rain, graupel, snow, and ice). The extended subgrid-scale hydrometeor transport scheme assumes input given in the form of marginal PDFs of vertical velocity and hydrometeor mixing ratios; in this study, these marginal distributions are provided by the cloud-resolving model. Conditional sampling and scaling are then applied to the marginal distributions to account for subplume correlations. The results demonstrate the potential use of the subgrid-scale hydrometeor transport scheme in an assumed PDF scheme to better represent the correlation between convective transport and subgrid-scale microphysics.
Xie, Shaocheng

Lawrence Livermore National Laboratory

xie2@llnl.gov

Clouds and Precipitation Simulated by the US DOE Accelerated

A new US Department of Energy (DOE) climate modeling effort is to develop an Accelerated Climate Model for Energy (ACME) to accelerate the development and application of fully coupled, state-of-the-art Earth system models for scientific and energy application. ACME is a high resolution climate model based on the Community Earth System Model (CESM) but with notable changes to its physical parameterizations. This presentation provides an overview on the ACME model's capability in simulating clouds and precipitation and its sensitivity to convection schemes. Results with using several state-of-the-art cumulus convection schemes, including those unified parameterizations that are being developed in the climate community, will be presented. These convection schemes are evaluated in both short-range hindcast mode and free-running climate simulations with both satellite data and ground-based measurements. Running climate model in short-range hindcast has been proven to be an efficient way to understand model deficiencies. The analysis is focused on those systematic errors in clouds and precipitation simulations that are shared in many climate models. The goal is to understand what model deficiencies might be primarily responsible for these systematic errors.
Zhang, Dan

Deutscher Wetterdienst
dan.zhang@dwd.de

Verification methodology for clouds and precipitation in high resolution models using 3D radar data

The project HD(CP)2 (High Definition Clouds and Precipitation for Climate Prediction) provides an unprecedented data set of high resolution model simulations (100m) along with a wealth of observations. In order to use this data set to improve the representation of clouds and precipitation in climate forecasts we must be able to quantify to what extent the high resolution simulations represent clouds and precipitation. Therefore, our work aims to develop verification methodologies for evaluating clouds and precipitation in high resolution model data representing small scale phenomena using three dimensional radar data. In addition, special interests are given to the uncertainties in the applied verification methodology itself as well as to the uncertainties in the precipitation forecasts compared to observations (radar). An object-based method 3D-SALH has been developed to be able to reveal the differences of the complex 3D characteristics between the forecasted and observed precipitation fields. The validation score consists of four distinct components that consider aspects of the structure (S), amplitude (A), location (L), and height (H) of the precipitation objects. Moreover, a fuzzy concept is applied to estimate a potential timing error in the forecasts, i.e. to detect a potential time shift between the simulated and observed precipitation fields. The detected timing errors can be separated from the errors in the simulated 3D characteristics. Furthermore, the uncertainties in the application of verification methodology with respects to the definition of precipitation object are also analysed. Different thresholds are used to define a precipitation object and the sensitivity of 3D-SALH to the definition is discussed. The methods are applied to several cases representing different meteorological conditions including one case with intense localized convection. Comparisons are performed between 3D radar data (reflectivity Z) from the German radar network and COSMO-DE (2.8km horizontal resolution) simulations as well as HD(CP)2 simulations (625m and 1250m).