BMBF Verbundprojekt

HD(CP)²

High definition clouds and precipitation for advancing climate prediction

Report on DKRZ Resources in 2021

Executive Summary

The report summarizes the individual reports of projects associated to the BMBF project HD(CP)^2 (Highdefinition clouds and precipitation for advancing climate prediction). The reporting covers the time period from 2021-01-01 to 2020-08-15. The individual project numbers are

- bm0834
- bm0852
- bm0982
- bb1018

The numbers for used computation time and used storage resources are taken as on 30 July 2021 unless stated otherwise.

The funding of the project HD(CP)^2 officially ended in September 2019 and but we think it is still useful for the climate community to keep HD(CP)^2 as a DKRZ consortia project alive.
The reasons are

- the analysis of the final results is still not finished yet and comparisons between observation and model data are still on-going, so that the scientific papers are in the process of being written or under review. This may require to keep data available for further analysis
- the HD(CP)^2 project S6 will continue at least until Feb 2022 and needs to run additional experiments, including data-intensive high-resolution NWP and LEM simulations with ICON, to simulate the NAWDEX context.

List of Content

1. Report Project bm834

Project title: HD(CP)2 module M, Cross-cutting Modelling Activities
Project lead: Kerstin Fieg (DKRZ)
Reporting period: 01.01.2021 - 15.08.2021

Overview

	Allocated for 2021	Consumed (15.08)	Consumed in total
Computing time (node*h)	4.250	2.312	
Temporary storage /work (GiB)	93.585	23.947	
Storage /arch (GB)	100.000	7.227	3.762.395
Long term storage /doku (GB)	5.000	-	116.291

In 2020 the project bm0834 was transformed from the main project account where most of the community experiments were performed, into a so-called data project, that manages, stores and distributes the core products of the individual HD(CP)^2 projects.

From November 2020 to August 2021, we reduced the consumption of LUSTRE /work space from 93.585 GiB to 23.947 freed nearly 75% of resources we consumed in 2020.

Since 2020 the project bm0834 uses MISTRAL computing time only for postprocessing tasks, thus we only asked for (and got granted) a very small amount of computing time (4.250 node*h). From that we only used 368 n*hours until 15. August 2021, 1.944 n*hours were cut.

After the official end of the HD(CP)^2 project end of Sept 2019 some of the S – subprojects received “Kostenneutrale Verlängerung” for three to six months and the Project S6, connected with the DKRZ account bb1018 the HD(CP)^2 project will continue until Spring 2022.

Nevertheless, because the production of new data slowed down and most of the HD(CP)^2 project core data are already moved to the data project bm0834 until end of 2020, there was no huge consumption of arch and doku space in 2021.

Nevertheless, we at least have the guarantee the availability of all data connected with papers for 10 years to fulfil the “Gute wissenschaftliche Praxis”.

It is planned to continue this storage and basic data management activity at least until end of the last HD(CP)^2 project bm1027 in Spring 2022.

2. Report Project bm852

Project title: HD(CP)2 Diagnostics and ice clouds in ICON
Project lead: Dr. Ulrike Burkhardt
Reporting period: 01.01.2019 - 31.10.2019

1. Overview

	Allocated for 2021	Consumed (15.08)	Consumed in total
Computing time (node*h)	11.220	664	
Temporary storage /work (GiB)	72.250	59.889	
Storage /arch (GB)	40.000	-	7.735
Long term storage /doku (GB)	15.000	-	.

2. Verbesserung der Eiswolkenphysik in ICON-GCM und Einfluss von Konvektion auf Zirrusbewölkung und das Wasserbudget der oberen Troposphäre (Burkhardt, b309022)

Due to a shortage of (wo)manpower the small amount of work planned within this subproject could not be performed anymore. We plan to turn this project into a data project after some minor analysis. We will apply for significantly reduced storage and by the end of the computing time period this subproject should be completely archived.

3. HD(CP)^2 - S1 TP2 Kondensstreifenzirren (Verma b309131, Burkhardt b309022)

In the last year, we have performed simulations of contrail formation within natural cirrus for an additional synoptic situation, a frontal passage over Germany. When examining the impact of the presence of preexisting cirrus ice crystals on contrail formation we found for this synoptic situation significant changes in the contrail ice nucleation and survival in the vortex phase. Therefore, we concentrated in our further work on examining those effects instead of making the planned long simulations. This slight change in the focus was necessary in order to round off the PhD thesis. The preparation of a publication and the thesis then meant that we could not go ahead with a few of the planned longer simulations.

We studied the effect of the natural cirrus on contrail ice nucleation and ice crystal loss in the vortex phase and studied the effect of the contrail formation on the cirrus optical depth for a high-pressure situation over Germany (24th April 2013) and a frontal passage (26th April 2013). In case of the frontal system we found a significant change in formation threshold temperature and therefore in the number of nucleated ice crystals in a contrail (Verma & Burkhardt 2021). Furthermore, we found that the natural cirrus properties affect the fraction of ice crystals surviving the contrail's vortex phase (figure 1). The entrained cirrus ice into the plume later sublimate together with the contrail ice crystals during the vortex descent. The ice mass that sublimates during the descent increases the plume relative humidity with respect to ice which causes an increase in the survival fraction of the contrail ice crystals. The higher the ice number concentration and ice water content in the cirrus the more ice crystals survive during vortex descent (Verma & Burkhardt 2021). The 26th April 2013 case cloud (frontal cirrus) has a large impact on the survival fraction because this cloud has high ice water content and ice crystal number concentration (figure 1b).

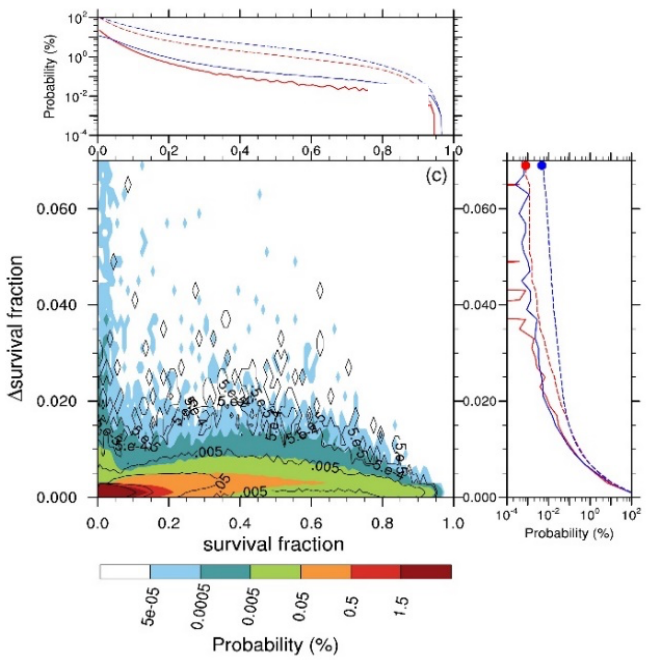

Figure 1: Joint probability distribution of contrail ice crystal survival fraction during the vortex phase when neglecting the impact of cirrus ice crystals and its change due to the sublimation of cirrus ice crystals for 26th April 2013 for 50% reduced soot number emissions. Additionally, the PDF of the fraction of surviving ice crystals (solid) and the associated cumulative PDF (dashed) when neglecting the impact of natural cirrus ice crystals (top) and its change due to the presence of cirrus ice crystals (right) is shown. A Brunt-Väisälä frequency of 0.012 s^{-1} (strong stability) has been assumed for all cases. Red lines indicate the probabilities when reducing the Brunt-Väisälä frequency to 0.005 s^{-1} (weak stability).

Furthermore, we analyzed the impact of contrail formation within the thick frontal cirrus and the thin cirrus during the high-pressure system over Germany. After about two hours, a large area of the cirrus has been perturbed due to contrail ice formation. The number concentration of contrail ice crystals is high compared to the surrounding cirrus ice crystal number concentrations and reaches up to values of 2x10^6 m^{-3} within cirrus (figure 2). However, some areas within the cirrus also have high number concentration of the ice crystals which likely indicates an ice nucleation event. The number concentration of contrail ice crystals after formation (nucleation and ice crystal loss in vortex phase) is larger in the thick frontal cirrus than within the thin cirrus because this cloud has a much larger ice water content and ice crystal number concentrations.

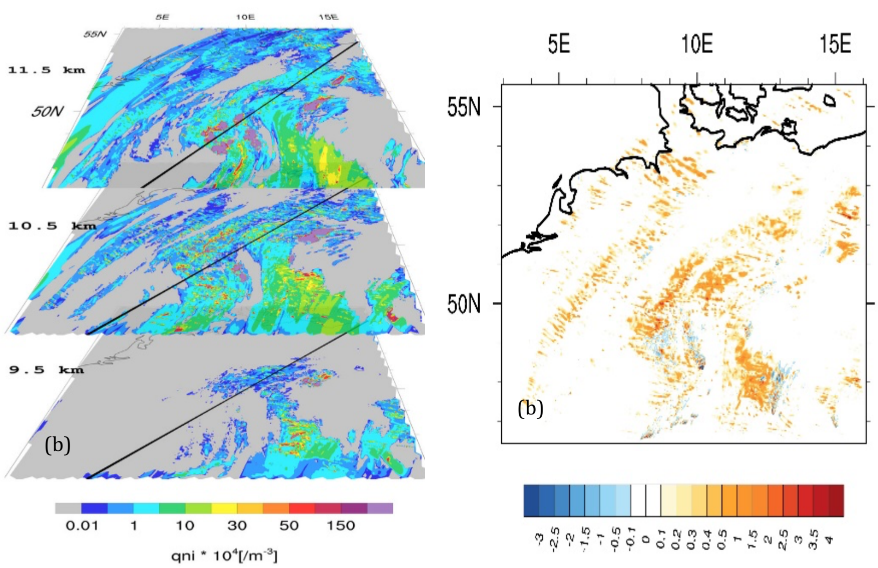

Figure 2: Number concentration of ice crystals in cirrus on 26th April 2013 after two hours of continuous air traffic (a) and change in cloud optical depth due to contrail perturbation (b).

We have estimated the change in the optical depth of the cirrus cloud after contrail formation. The perturbation of the cirrus ice crystal concentrations due to contrail formation causes a significant perturbation in cirrus optical depth. The optical depth of the cloud is dependent on the effective radius (ice crystal habit and size) and ice water content in the cloud. We calculate the change in cirrus optical depth assuming an ice crystal habit mix representative for young contrails (Schumann et al., 2010) and a log-normal particle size distribution. The change in the optical depth due to contrail formation within cirrus reaches values of up to 3.0.

We expect to still perform longer simulations to study the life cycle of the contrail perturbed cirrus for both synoptic conditions and analyze how long these effects can be seen until October.

4. References:

Schumann, U., B. Mayer, K. Gierens, S. Unterstrasser, P. Jessberger, A. Petzold, C. Voigt, and J-F. Gayet. " Effective Radius of Ice Particles in Cirrus and Contrails". *Journal of the Atmospheric Sciences* 68.2 (2011): 300-321. < https://doi.org/10.1175/2010JAS3562.1>. Web. 14 Jul. 2021.

Verma, P. and Burkhardt, U.: Contrail formation within cirrus: high-resolution simulations using ICON-LEM, Atmos. Chem. Phys. Discuss. [preprint], https://doi.org/10.5194/acp-2021-497, in review, 2021.

Costa-Surós, M. et al - Detection and attribution of aerosol-cloud interactions in large-domain large- eddy simulations with ICON, 2020.

Rybka, H., Köhler, M., Seifert, A., Burkhardt, U., Arka, I., Bugliaro, L., Reichardt, J., Görsdorf, U., Meyer, C., Strandgren, J., Horvath, A. - High-resolution modeling of high-CAPE summer convection - role of ice microphysics and large-scale forcing, in review.

3. Report Project bm982

Project title: HD(CP)2-II S4 (Land Surface Heterogeneity)
Project lead: Stefan Poll
Reporting period: 01.01.2021 - 01.08.2021

Overview

	Allocated for 2021	Consumed (15.08)	Remarks
Computing time (node*h)	75650	25001	Cut Q1 /Q2: 15643
Temporary storage /work (GiB)	38250	28720	
Storage /arch (GB)	45000	0	In total: 28199
Long term storage /doku (GB)	3000	0	

15643 node hours are expired mainly due to changes in the work-flow caused by the COVID-19 outbreak and the change of Dr. Shweta Singh from the Karlsruhe Institute of Technology (KIT) to the University of Frankfurt.

Activities Project bm0982

In the reporting period, the investigation of land-surface heterogeneity has been continued. In particular the interaction between land-surface heterogeneity and convection was analyzed and a tuning approach to account for dynamical effects of land-surface heterogeneity was invented as well as for a model inter-comparison study of real-world simulations are performed.
Based on the studies with the use of computing time granted of the project 982, one publication were published, one additional are recently under review and two publications are in active process in 2021.

Convective Precipitation in Dependence on Model and Land-surface Resolution

The study have been continued from the previous year. The focus of this study is to investigate the impact of model grid spacing and land-surface resolution on clouds and precipitation using ICON-LEM simulations and to determine the processes which result into the differences across model grid spacing (Δh). It furthermore explores the capability of ICON - in dependence of grid spacing and land-surface resolution - to simulate those processes, which are responsible for the triggering of convective precipitation.

At first, the geographical areas with a hierarchy of orography and associated deep convection Germany-wide are selected. These three regions are: i) the flat terrain near Berlin, ii) the isolated mountain range in the central part of Germany, called as Harz mountains, and iii) the complex terrain, the Black Forest mountains. Six suitable days with low synoptic forcing, two for each area, are selected. After selecting the areas and suitable cases, the ICON-LEM simulations are designed with six model grid spacings in a nested setup called as control runs: NWP (Δ_x=5000 m, 2500 m), LES (Δ_x=1250 m, 625 m, 312 m and 156 m) with the same model configuration. The control run Δ_x=156 m is named reference run, and all results are compared with respect to this simulation. Moreover, the land-surface sensitivity experiments at a scale of 1250 m and 5000 m have been performed in order to understand the relative impact of land-surface resolution on convective precipitation. That gives in total six sets of control runs and 30 sets of land-surface sensitivity experiments.

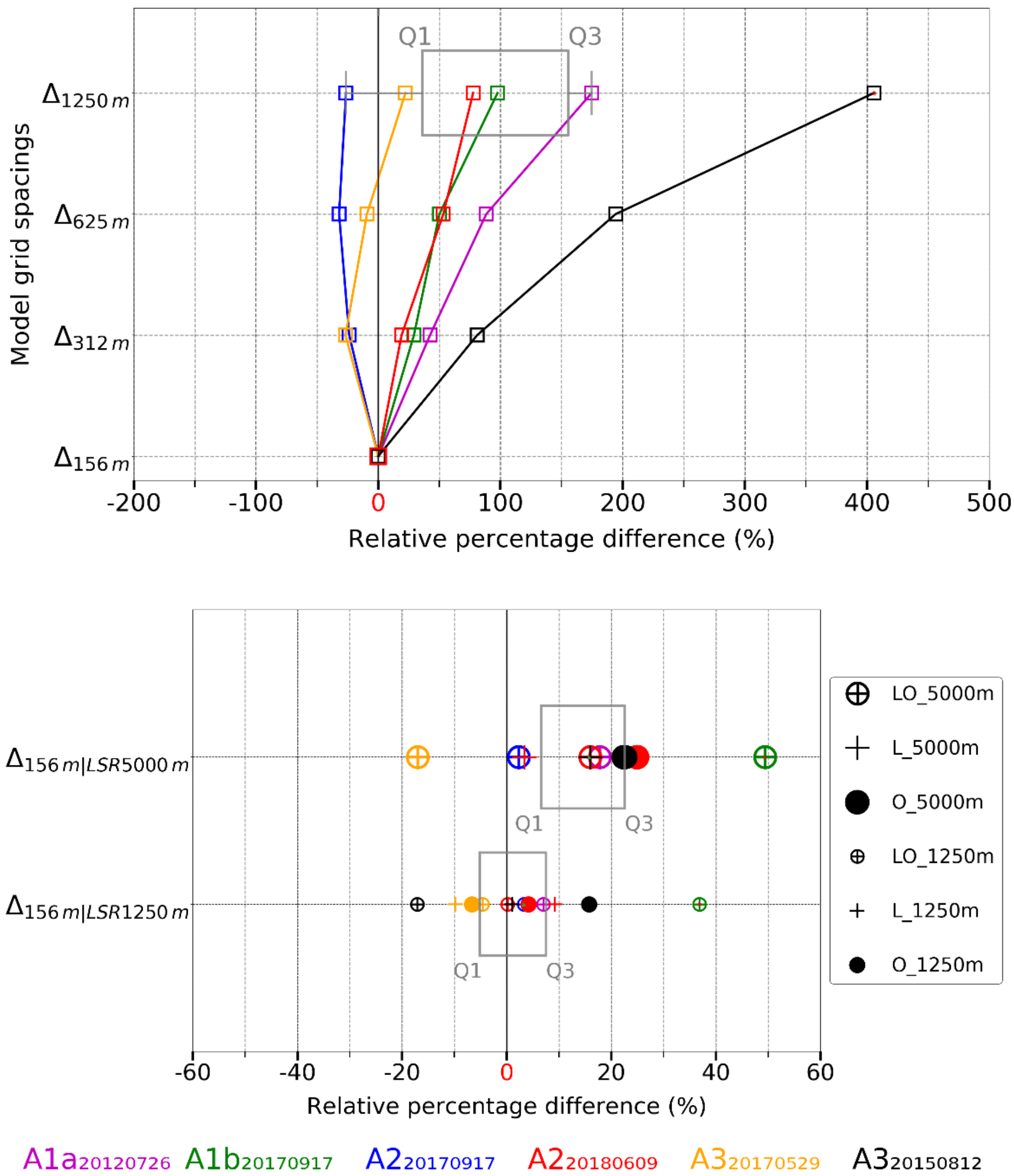

Figure 1: Relative percentage difference of convective precipitation of coarser simulation with LES reference (Δ_x=156 m) in dependence of model grid spacing (upper row) and land-surface resolution (lower row). Days and domain of investigation in colour.

The results show that the domain average of accumulated precipitation for most of the cases decreases systematically across the LES grid spacings from Δ_x1250 m to Δ_x156 m (Fig. 1). More specifically, the differences of the areal mean precipitation between the control runs (Δ_x=1250 m, Δ_x=625 m, Δ_x=312 m) and the reference run normalised by the reference run can be quite considerable, i.e. the values are in the range of -26 to 400 % with the 75th percentile of 155 %. It is also found that the precipitating cells in Δ_x1250 m are typically more intense in comparison to the finer LES model grid spacings. Additionally, the onset time of precipitation can differ by 1 to 2 hours (normally precipitation starts earlier in Δ_x1250 m than Δ_x156 m). This is a consistent model behaviour found in the precipitation patterns simulated for all cases. The differences in the real mean precipitation due to the modifications of respective land-surface resolutions are considerably small. The relative differences range from about -17 to 37 % with the 75th percentile of 7 % with the land-surface resolution of 1250 m and increases to a range of -17 to 49 % and the 75th percentile of 22 % with the land-surface resolution of 5000 m. Some parts of the above results are published in Stevens et al. 2020.

This offset in model behaviour gives a hint that there is a lack of convergence in simulated mean precipitation at least for model grid spacing $\geq\Delta_x$156 m. Therefore, we performed a test model run at the grid spacing of 75 m for one of the case study at mistral.

These results are published "Sensitivity of convective precipitation to model grid spacing and land-surface resolution in ICON" in QJRMS (Singh et al., 2021).

Grid Resolution Dependency of Land Surface Heterogeneity Effects

Land surface heterogeneity exerts a strong control on atmospheric boundary layer (ABL) evolution by spatially varying the distribution and partitioning of surface energy fluxes. In the terra incognita range of model resolution, numerical effects may additionally impact the simulated ABL states, which is the focus of this study.

We extend the study of last year to analyse grid resolution effects for a mesoscale strip-like land surface inhomogeneity in land cover, soil moisture or both combined, embedded in an elsewhere homogeneous landscape. The numerical sensitivity study is conducted with the global weather prediction model ICON (Icosahedral Nonhydrostatic model) with the ICON-LEM (ICON Large-Eddy-Model) simulation as a benchmark.

The ICON model is used in NWP and LEM mode to simulate the PBL evolution with varying grid resolutions and land surface heterogeneities using an idealized setup for an area of 144 x 80 km with double periodic boundary conditions. The (horizontal) domain is enlarged along the mean wind direction to minimise boundary affects in the central analysis area (containing the 20 km wide strip of inhomogeneity), by keeping it sufficiently distant from the boundaries. One LES resolution (50 m) and five NWP grid resolutions ranging from 300 m to 4800 m with a stepwise coarsening of the grid resolution by a factor of two, two atmospheric conditions, and three land heterogeneity of the strip.

While simulations with the NWP scheme approach the ICON-LEM simulations when refining the spatial grid towards the ICON-LEM resolution, the model generates artificial circulations leading to boundary-layer height oscillations when the horizontal grid resolution approaches the length scale of the largest eddies in the boundary layer (Fig. 3). In our kilometre-scale simulations the edges of land surface heterogeneity may trigger such artificial circulations. Model-induced circulations are most dominant under calm background wind and weak thermal contrasts. Model-induced circulations are problematic, because they may change the atmospheric state, and depending on the degree of the heterogeneity they may dominate the atmospheric response in terra incognita simulations and exaggerate the effect of land surface heterogeneities. The induced change of the ABL might affect the development of clouds, which are preferably initiated along the updraft regions and might cause convective initialization above the PBL and thus severely affect forecast skill.

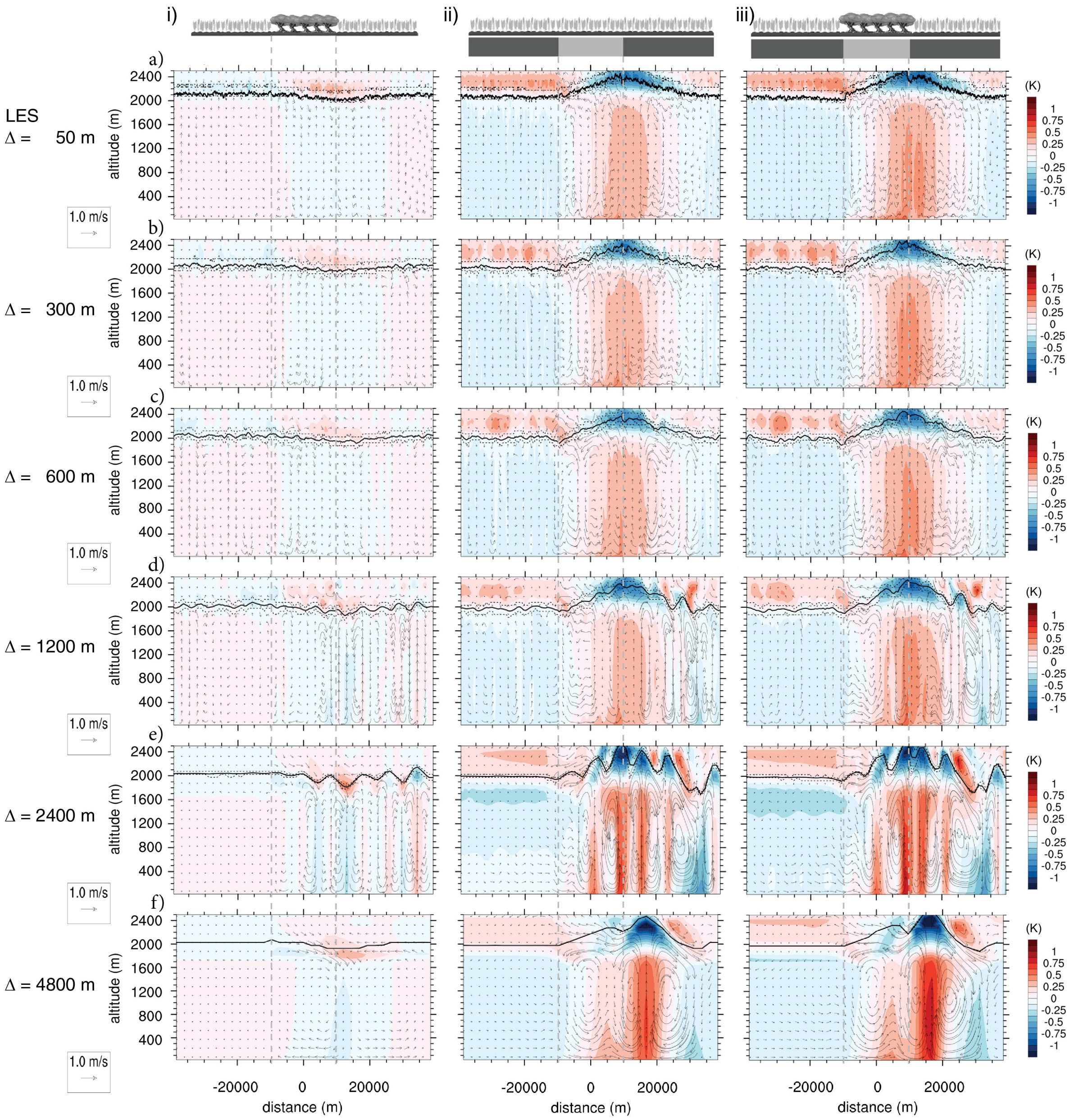

***Figure 2**: Vertical cross-section of virtual potential temperature and wind anomaly for each height level for cell condition three hours after initialization averaged in y direction. The sub-figures in the rows show the results for the LES (reference, Δx= 50 m) and the five NWP simulations with resolutions Δx= 300 m, Δx= 600 m, Δx= 1200 m, Δx= 2400 m and Δx= 4800 m. The columns refer to the results for the three land surface heterogeneities. The black thick solid line indicates the PBL height with the 25% and 75% quantile as dotted lines.*

ABL scheme tuning using the asymptotic turbulent mixing length scale for its effect on reducing the artificial model circulations. An ensemble of simulation is performed with changes in soil-moisture heteorogeneity as well as the background wind to account for different strength of thermal heteorogeneity and changes in synoptic condictions. With the mean of a non-linear least square a ABL tuning scheme for dynamical grid resolution effects of land surface heterogeneity was found. These circulations are effectively attenuated by using a two-dimensional field of asymptotic turbulent mixing length scale corresponding to the land surface heterogeneity, leading to an improvement of boundary layer states.

This study is under review "Grid Resolution Dependency of Land Surface Heterogeneity Effects on Boundary Layer Structure" in QJRMS (Poll et al., 2021).

Model Inter-comparison Study

A model inter-comparison study between state-of-the-art atmospheric models has been started in the area of the southern great plains the United States of America. ICON-LEM will be compared with the Weather Forecast and Research model (WRF). The aim is the identification of strengths and weaknesses on ABL development of the commonly used forecast models. The ICON-LEM simulations are nudged into coarser ICON-NWP simulations forced with IFS data. The model comparison is chosen to make use of the LAFE measurement campaign, which took place in August 2017. The production of these simulations already started in July 2021 and will be finished before HLRE-3 Mistral is decommissioned.

References

Poll S., P. Shrestha, C. Simmer, 2021, Grid Resolution Dependency of Land Surface Heterogeneity Effects on Boundary Layer Structure, *QJRMS*, under review

Poll S. et al., Inter-comparison of real world Large-Eddy-Simulation for the LAFE measurement campaign, in preparation

Singh S., L. Gantner, N. Kalthoff, 2021, Sensitivity of convective precipitation to model grid spacing and land-surface resolution in ICON. *QJRMS*

4. Report Project bm1018

Project title: HD(CP)2 S6 Cloud-radiative interactions with the North-Atlantic storm track
Project lead: Aiko Voigt
Reporting period: 01.01.2021 - 15.08.2021

Overview

	Allocated for 2021	Consumed (15.08)	Consumed in total
Computing time (node*h)	172.125	91.000(+49.000 cut)	
Storage /work (GiB)	416.000	514.000	
Storage /arch (GB)	8.000	255.000	192.500
Long term storage /doku (GB)	-	-	

Preface

We have continued to study how cloud-radiative effects shape the extratropical storm tracks and their response to climate change. To this end, our main tool has remained the ICON model in global low-resolution and regional high-resolution setup.
2021 has also seen a major change in that Aiko Voigt has joined University of Vienna as a Full Professor for Climate Science. Yet, the BMBF young investigator group that underlies this project is funded and will continue to work until February 2022.

Due to the move of Aiko Voigt to Vienna and other personnel changes we have used less resources than anticipated. We will continue to perform ICON simulations and archive part of their results, yet we will not use all of the allocated resources.

Note: As in February 2022 the BMBF group will come to an end, for 2022 we will only apply for postprocessing resources and work space.

Global ICON-A simulations

In the context of a MSc thesis, we performed and analysed global Amip-like ICON-A (ICON with physics package for climate simulations, based on ECHAM6) simulations with prescribed sea surface temperatures. We implemented the cloud- and water vapor-locking method into ICON-A, and we also implemented a slab ocean into the model. Both methods are new to ICON-A. We have now finished the necessary test simulations and will perform production simulations starting in September 2021. These will run until December 2021 and will be finished before HLRE-3 Mistral is decommissioned.

Analysis of ICON-NWP LAM simulations over the North Atlantic

We have continued to analyse the ICON-NWP LAM simulations that were performed over the North Atlantic for the NAWDEX field campaign in previous years. This line of work has two main components. First, we continued our work on the warm conveyor belt of NAWDEX cyclone Vladiana. We identified some weaknesses in our prior analysis, requiring us to rerun

LAGRANTO trajectories. This has led to a substantial delay, but the corresponding paper is now taking shape to be submitted in fall 2021 (Choudhary and Voigt, to be submitted). Moreover, we have analysed the whole set of NWP simulations during two hackathons in 2021 that have built upon 2 hackathons that we already held in 2020. For these, we made extensive use of jupyterlab of DKRZ/Mistral. A paper is currently in preparation as a group effort, with a planned submission in fall 2021 (Voigt et al, to be submitted).

ICON-NWP LAM simulations over the Asian Monsoon Region

Among tropical clouds, our previous results identified upper-level ice clouds as having an important handle on midlatitude circulation and its response to global warming. Acccurate simulation of these ice clouds is challenging, as atmospheric ice crystals can have a huge range of sizes and shapes and undergo a variety of collection and collision processes. We thus have focused on constraining the sensitivity of cloud-radiative heating rates to various uncertainties in ice microphysics schemes. We have used a series of high-resolution, limited-area ICON simulations with different microphysical settings, as well as a new online trajectory module to quantify the range of cloud-radiative heating rates generated by tropical ice clouds. The project has contributed to an NSF Partnership for International Research and Education (Award #1743753), led by the University of Chicago, and has benefitted from collaborations with the University of Mainz and the Forschungszentrum Jülich, making use of observations obtained in the StratoClim campaign. A first paper has appeared as Sullivan and Voigt (2021), a second paper is currently in preparation.

The first paper was published in the new open-source Nature journal Communications Earth & Environment (Sullivan and Voigt, 2021). The key takeaway of this work is a dramatic control of ice microphysics on large-scale radiative outputs (Fig. 1). More precisely, the cloud-radiative heating rates between 500 and 200 hPa can change by a factor of four and the domain-mean daily-mean outgoing longwave radiation can change by 30 W m^{-2}, when we adjust factors like the ice crystal size or the conversion of snow to ice. Along with this quantification of radiative sensitivity to ice microphysics, our article digs into the microphysical schemes to provide mechanistic explanations for why heating rates and fluxes change the way they do.

For the second paper, we have continued to use (and debug) a trajectory module within ICON (developed by A. Miltenberger), particularly its restart capabilities and implementation in limited-area setups (Trajectories are terminated when they hit simulation boundaries.). We then ran two sets of trajectories with the one- versus two-moment microphysics active. Approximately 10^5 trajectories were launched from a patch in the Sichuan basin and flowed over a 50-hour lifetime toward the StratoClim Flight 7 measurements around Kathmandu and eastern India. These trajectories were are also used to drive a separate, offline ice microphysics scheme called ClaMS-ice. We continue to analyze the output of our trajectory simulations and writing up a second manuscript (Sullivan et al., in prep.). In addition to the

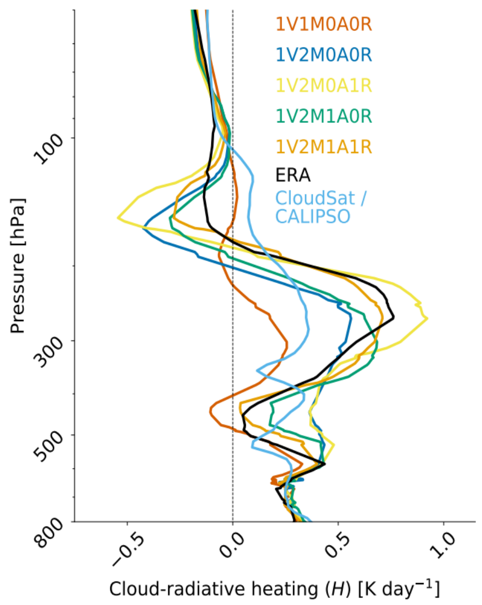

Fig. 1: Cloud-radiative heating rates for various ICON-NWP simulations versus the ERA reanalysis (black) and the CloudSat satellite climatology (light blue).

thermodynamic biases mentioned above, we find large shifts in the temperature and relative humidity dependence of the ice mass mixing ratio and ice crystal numbers calculated along the trajectories. We are working to understand these differences in terms of sedimentation tendencies and the predicted partitioning of heterogeneous-homogeneous nucleation

Analysis of ECHAM6 and ICON Transpose-AMIP global simulations

We have analysed the Transpose-AMIP simulations with ECHAM6 and ICON-NWP that were previously done by colleagues within HD(CP)2. Based on previous PTE analyses by others, we applied the PTE diagnostic approach (PTE = surface pressure tendency equation) to the NAWDEX T-AMIP simulations to probe the physical reasons behind model biases in cyclone strength, with a focus on diabatic processes. The idea of PTE is that the surface pressure tendency (Dp) of a cyclone, results from changes in geopotential (DΦ) and integrated temperature tendency (ITT). The ITT term can be further horizontal temperature advection (TADV) and vertical motions (VMT) and diabatic processes (DIAB). We find that the ITT term is smaller in ICON-NWP compared to ERA5; indicating a larger contribution of the temperature changes due to total surface pressure tendency budget in the later (Fig. 2, first row). This results mainly from stronger diabatic processes in ERA5 compared to ICON-NWP (Fig. 2, second row), providing an explanation for the weaker cyclones in ICON-NWP compared to ERA5 (Fig. 2, third row). We plan to finish this analysis until Feb 2022. Different to our original work plan, we will not perform our own T-AMIP simulations

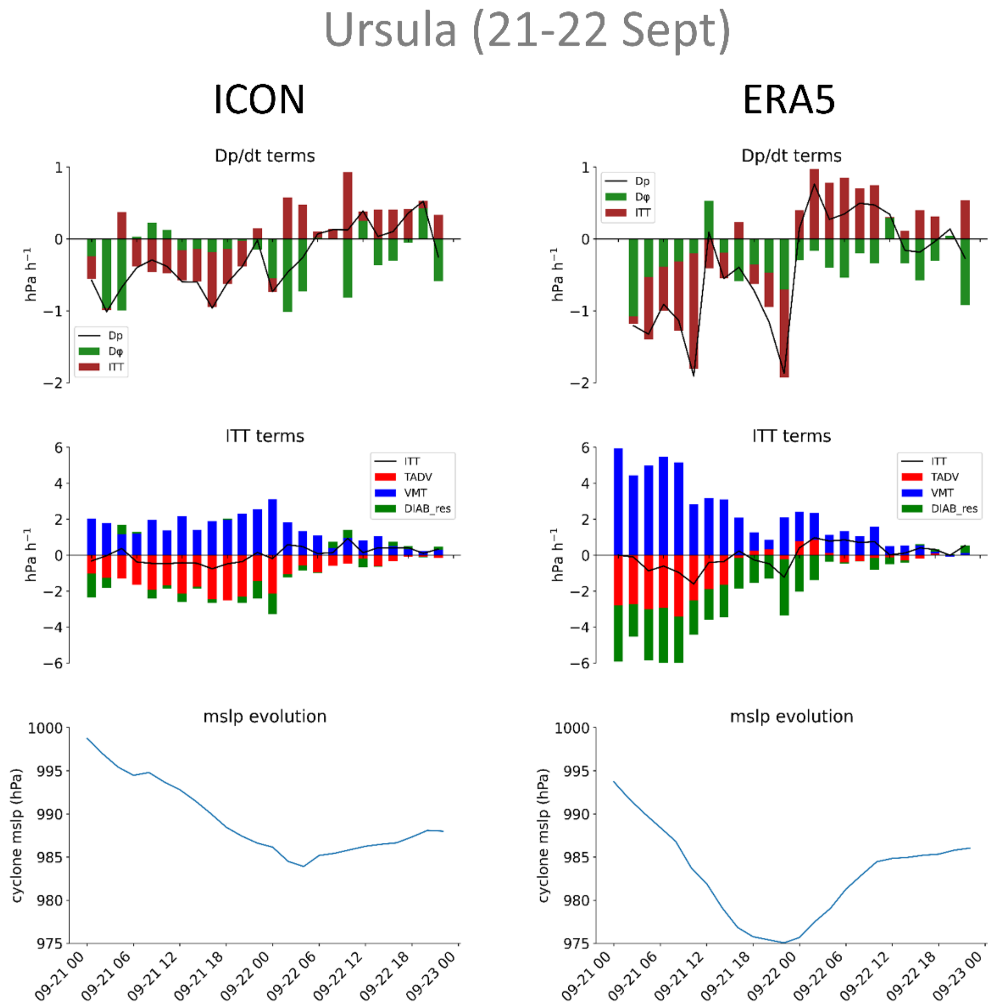

Fig. 2: PTE based analysis for one of the NAWDEX cases- cyclone Ursula- which occurred during 21-22 September, 2016. PTE is calculated along the cyclone track and averaged over 3°×3° box centered around the cyclone core. First row: surface pressure tendency (dp/dt) and its decomposition. Second row: decomposition of the ITT term. Third row: core pressure development of the cyclone as MSLP change. The values shown here are instantaneous at every 2-hour interval. The results here are presented only for the ICON simulation with the first initialization date.

Publications

Albern, N., A. Voigt, and J. G. Pinto, 2021: Tropical cloud-radiative changes contribute to robust climate change-induced jet exit strengthening over Europe during boreal winter, Environ. Res. Lett. 16, 084041, doi: 10.1088/1748-9326/ac13f0.

Choudhary, A., and Voigt, A.: ICON simulations of cloud-diabatic processes in a warm conveyor belt of an extratropical cyclone: A case study, to be submitted to QJRMS in fall 2021.

Sullivan, S., and A. Voigt, 2021: Ice microphysical processes exert a strong control on the simulated radiative energy budget in the tropics. Comm. Earth & Env. 2 (137), doi:10.1038/s43247-021-00206-7.

Sullivan, S., A. Voigt, A. Miltenberger, C. Rolf, and M. Krämer, Constraining feedbacks to evaluate the impact of ice microphysics on cloud-radiative heating, in preparation.

Voigt et al.: Controls on simulated atmospheric cloud-radiative heating over the North Atlantic, to be submitted to JGR-A in fall 2021.