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Meeting Summary: Exploring Cloud Dynamics with Cloud Model 1 and 3D Visualization – insights from a University Modeling Workshop

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Abstract. We introduce an innovative two-week educational block course held at the University of Bonn during the 2023 winter semester, focusing on Cloud Model 1 (CM1) and its convection-permitting capabilities. During the course, students gained essential skills in setting up and customizing CM1 simulations on high-performance computing clusters, while delving into deep moist convection dynamics. An additional introduction to three-dimensional visualization software allowed the participants to transform numerical data into compelling visualizations, deepening their insights into cloud dynamics. Students applied their gained knowledge in research projects of their own choice that will be presented here and in the supplementary material.

1 Motivation

Thunderstorms hold a unique fascination for students of the atmospheric sciences. At the same time, numerical modeling plays a vital role in meteorology (Coiffier, 2011). Numerical weather prediction is a typical example of a high performance computing (HPC) application, commanding substantial computational resources (Vourlioti et al., 2023). Leading meteorological research and forecast centers such as the European Centre for Medium-Range Weather Forecasts (ECMWF), the National Center for Atmospheric Research (NCAR), the German Weather Service (Deutscher Wetterdienst, DWD), the Swiss National Supercomputing Centre (CSCS), MeteoSwiss use HPC systems to provide high-resolution weather (and climate) forecasts and reanalysis data (Nakaegawa, 2022). Hence, skills regarding the set-up, simulation, and analysis of numerical weather (and climate) models on HPC clusters are often essential for a further career in meteorology. Here, we present an innovative solution that combines the development of these skills with the motivating topic of deep moist convection.

In this work, we will present results from a two-week intensive introductory modeling course of Cloud Model 1 (CM1) accompanied by an introduction to a three-dimensional (3D) visualization software. Students mastered CM1 simulations on an HPC cluster and undertook their own research projects in the second week (see section 2 for more details on the course topics). CM1 is an up-to-date, convection-permitting, non-hydrostatic numerical model that allows the study of atmospheric phenomena in idealized setups (Bryan and Fritsch, 2002; Bryan, 2021). CM1 can be run on single computers as well as on

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high-performing computer clusters in parallel with grid spacing ranging from tens of kilometers down to a few meters (e.g. Orf et al., 2017, who run a simulation of a tornado with 30 m grid spacing). It is available for download free of charge and its license allows the users to modify the source code according to their problems. It has been used to study tropical cyclones, mesoscale convective systems, supercells and thunderstorms, but also non-hydrostatic mountain waves, sea-breezes and low-cloud systems in an idealized way (see Bryan, 2021, for an extensive list of publications citing CM1). In comparison to more realistic models it is possible to study cloud systems in an idealized way, with systematic changes to the model environment such as topography and atmospheric parameters. CM1 is commonly used in severe convective storms research, predominantly in the U.S., and a large scientific community is available for questions regarding the code, and exchange and discussion of results. CM1 is an ideal model for mastering the fundamental essentials required for model set-up, initialization, numerical integration, and output generation. Furthermore, it can serve as a valuable introduction to more complicated and realistic models such as the Weather Research and Forecasting Model (WRF), the Consortium for Small-scale Modeling (COSMO) model, the Icosahedral Nonhydrostatic Weather and Climate (ICON) Model and others.

Next to the introduction to CM1, the block course set a focus on visualizing the results. Data visualization is indispensable in atmospheric science. With help of weather charts at different pressure levels, cross sections and vertical profiles, meteorologists explore the atmosphere's three-dimensional state for informed forecasts. Additionally to two-dimensional weather charts, three-dimensional visualization aids in understanding intricate processes like flow dynamics and development. Rautenhaus et al. (2017) gives an overview over visualization techniques commonly used in operational weather forecasting and in meteorological research and emphasize its importance for – among others – visual mapping of observations and simulation, flow analysis and its temporal evolution, the detection and tracking of atmospheric features as well as the analysis of uncertainty in simulations. Although very important, the topic of visualization is rarely covered in lectures of meteorology. Since three-dimensional visualization has the potential to give additional insights into the dynamics of atmospheric phenomena, we covered this topic in the course, too.

In this work, we want to advertise the course material and present the outcome of the modeling course to a greater community. The idea is that this paper can help to create own model workshops based on the freely-available course material. Moreover, we want to share results of the student's projects that showcase the applicability of the course material to realize own research ideas. This paper is organized as follows: A course overview is given in chapter 2. A brief overview over the student's projects is presented in chapter 3 and in greater detail in the supplementary material. A summarizing conclusion is given in chapter 4.

2 Course design and course requirements

The course covered vital topics, teaching students model compilation, HPC operation, code modification and data visualization within two weeks. In the first week, students learned the essentials of running and visualizing CM1 simulations on an HPC, applied to specific problems such as the supercell simulation. In the subsequent week students mainly worked on independent small-scale research projects, building upon their acquired knowledge. In order to successfully pass the course, each student was mandated to submit a report of about 20 pages on their personally selected subject. This report served as documentation

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Table 1. Overview over the course topics and timetable of the 2 weeks CM1 and visualization modeling course.

Time	Day 01	Day 02	Day 03	Day 04	Day 05
Morning	HPC and Slurm, Vim, scp/ssh	Compiling CM1 and first (pre-configured) supercell simulation	Introduction to ParaView (continued); Visualization of supercell data	External sounding, supercell literature Setting umove and vmove in namelist (moving domain)	Changes to the source code (continued) Presentation and discussion of results (so far)
Afternoon	CM1 source code and website	Introduction to ParaView	governing equations of CM1; Simulation control via the namelist	Changing the appearance of the warm bubble in the CM1 source code	Terrain (idealized)

Time	Day 06	Day 07	Day 08	Day 09	Day 10
Morning	Terrain (continued); Real terrain	Restarts; How to deal with error messages	Project	Project	Project
afternoons	Real terrain (continued)	Project: Work on a presentation of own project idea (presentation of idea and a rough project plan, 3 slides)	Project	Project	Work on an updated presentation of own project (state up to this day); Planning of the final report

showcasing their competence in modifying and executing the model, as well as visualizing self-generated data. Refer to Table 1 for comprehensive course details and the timetable. The course is published under a Creative Commons License as open education resource (OER Schielicke, 2023). The course is a stand-alone course that was originally planned for master students, but also advanced bachelor students (5th or 6th semester) were encouraged to take the course as an extracurricular activity. In March 2023, four students finished the course, two of them were still Bachelor students. Only one of the students had prior experience with CM1. Generally, the course is best accompanied by a course in convective or mesoscale meteorology, as this aids in the interpretation of the produced data.

In this work, we use Cloud Model 1, version cm1r21.0 (released 20 April 2022), which was the most current version available during the workshop. We compiled CM1 to enable obtaining output in a netCDF format, which facilitates subsequent analysis. Note, that the CM1 model simulations are generally initialized with a single vertical profile that determines the initial atmospheric conditions of the whole domain. Although the course was designed to set-up the model on a specific HPC cluster (bonna of the University of Bonn), users of single-computers are encouraged to run through the course material, too. However, they are referred to the CM1 website to learn what is required and how to compile the model for single computers. Unix/Linux environment makes it easier to use, although it is also possible to run CM1 on a Windows (or Mac) computer, too.

As visualization tools the focus lay on ParaView and Ncview, which were both already available at the HPC cluster Bonna of University Bonn. To get a fast overview over the data, the two-dimensional (2D) visualization tool Ncview proved to be helpful as a start before further more computationally costing three-dimensional (3D) tools were used. Ncview is a visual browser that allows a fast examination of netCDF data (Pierce, 2021). On the other hand, ParaView is an open source 3D visualization software. It can be used to interactively analyse large data sets, but could also be used via scripts (Ahrens et al., 2005; Ayachit, 2015). It is well documented online and students had two half days to work through the online material (ParaView Developers, 2020). One of the students had prior expertise in VAPOR (Visualization and Analysis Platform) of the National Center for Atmospheric Research's Computational and Information Systems Lab. VAPOR is another 3D visualization tool that can be used either interactively or via scripts to produce animations or images (Li et al., 2019; Visualization & Analysis Systems Technologies, 2023). It has similar advantages as ParaView with a broad user community and extensive online documentation. Hence, the student used VAPOR for the visualizations, but also worked through the ParaView course material.

Due to time constraints, we could not cover all topics. An incomplete list of topics not covered or only partially scratched are: (i) the Courant-Friedrichs-Lewy (CFL)-criterion, (ii) dealing with errors and error messages, (iii) testing more pre-configured test cases, (iv) releasing parcels, (v) restarts with higher resolution, (vi) exploring the difference between large-eddy simulations (LES) and direct numerical simulations (DNS), and so forth. A follow-up course is in planning.

3 Students projects

Regarding the education of students, true achievement is defined not only by theoretical knowledge acquisition but also by its transformation into real-world solutions. In this section we will give a brief overview over the students' research projects that were part of fulfilling the course requirements. A detailed description of the projects including two- and three-dimensional visualizations can be found in the supplementary material.

3.1 Influence of topography on deep moist convection under weak and mesoscale lifting conditions

As an active storm chaser in western Germany, the participant focused the research on how local topography affects intense storms, particularly over mountains. Using numerical weather prediction models and varied resolutions, the goal was to replicate convective storm development in cases with weak and strong lifting mechanisms. Comparing storm intensity and precipitation rates, the finding is that weaker lift led to more intense storms over mountains, aligning with his observations. Visualization software aided in showcasing storm structures and vorticity patterns, providing practical insights for nowcasting and underlining the importance of local topography in convective storm development. Fig. 1 illustrates the connection between downdrafts

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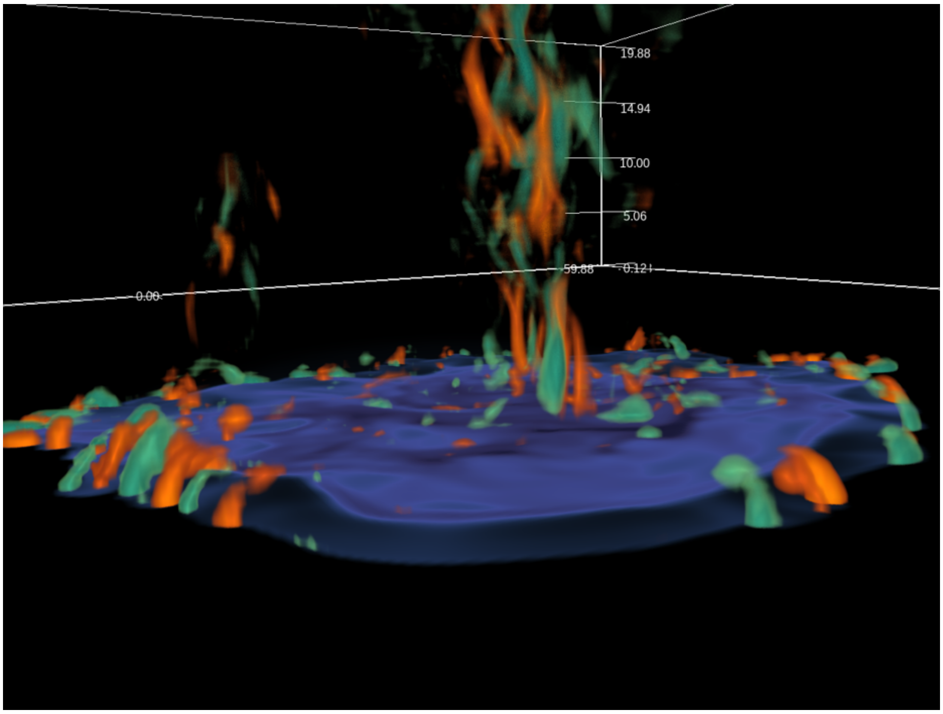

Figure 1. 3D-visualization of the cold pool formed by short lived cells in a weakly dynamic environment. Displayed are the negative potential temperature perturbation in the lowest model-level (blue, -0.5 K isotherm); and vorticity volumes (orange: $0.013s^{-1}$; turquoise: $-0.013s^{-1}$). Figure was plotted by Aaron Sperschneider using VAPOR.

and the emergence of vorticity patches at the periphery of a coldpool, further enriching the study (see also Supplementary Material, Section 1.1).

3.2 Study of different lifting processes and modified soundings of the Moore/Oklahoma tornado outbreak on 3 May 1999

The Moore, Oklahoma tornado outbreak on May 3, 1999, is investigated focusing on storm initiation mechanisms and environments. The study used the CM1 model, exploring different setups and lifting mechanisms to understand storm initiation and structure. It emphasizes the importance of modifying soundings for accurate outcomes, particularly noting that the original sounding failed to initiate cells. Higher-resolution simulations were also conducted to study the three-dimensional structure of supercells. Fig. 2 illustrats a snapshot of a simulated supercell, showcasing typical supercell characteristics like rotating updraft and a pronounced hook echo. Suppl. Fig. 6 (see Supplementary Material, Section 1.2) provides a detailed view of the lower parts of a right-moving supercell, revealing a tornado-like vortex and a lowered wall cloud. The project highlights the significance of initiation mechanisms and sounding parameters in influencing convection patterns, especially when studying

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supercells using reanalysis data or observational profiles. The study combines knowledge of severe convective storms with insightful visualizations to interpret model data, emphasizing essential aspects of severe weather research.

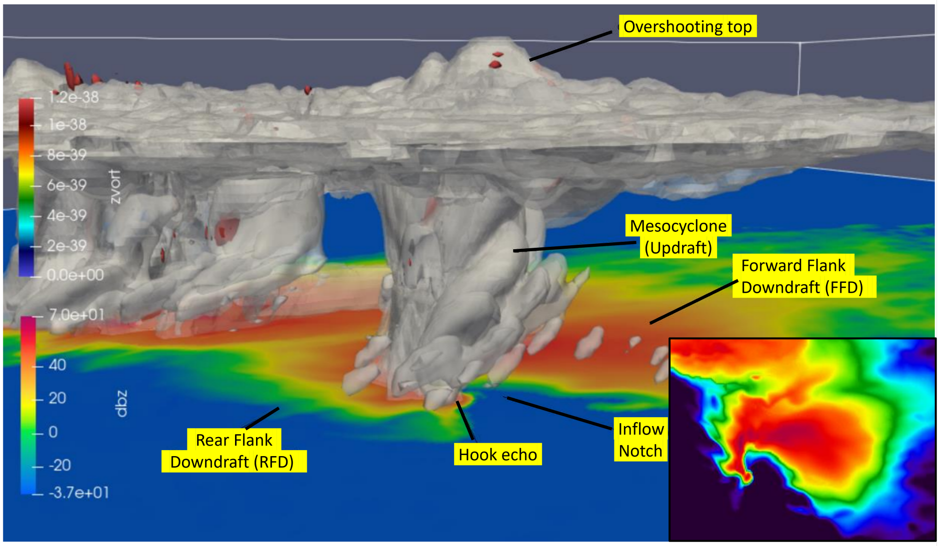

Figure 2. 3D visualization of a right-moving supercell with its typical characteristics. Shown is the reflectivity at 250 m (in dBZ, color-shaded at the surface for the 250 m level; and in the inset (2D plot) at 750 m). Whitish colors represent the cloud composed of the mixing ratios of cloud particles (q_c), graupel (q_g) and ice (q_i). Inside the clouds, colored shadings represent positive vertical vorticity ζ surfaces with values of $\zeta = 0.03s^{-1}$ and $\zeta = 0.05s^{-1}$. Figure was plotted using ParaView (3D) and ncview (2D) by Jerome Schyns.

3.3 Comparing the development and microphysical composition of high-humidity/classic/low-humidity supercells

The project investigates supercell behavior in varying moisture environments (low, classic, high-humidity) with and without considering terrain. Using CM1 simulations and modified Weisman-Klemp supercell soundings (Weisman and Klemp, 1982), the study compares radar reflectivity and mixing ratios of rain and graupel in six different set-ups. Notable findings include the importance of initial humidity on supercell's microphysical composition and development as well as the role of terrain in accelerating supercell development. In low-humidity conditions, supercells were smaller and exhibited slower development, emphasizing humidity's role in precipitation processes. Overall, the project illustrates how environmental factors significantly impact storm development and microphysical processes, providing valuable insights for both research and education. The reader is referred to Supplementary Material, Section 1.3, for more details.

3.4 Visualization of precipitating and non-precipitating shallow cumulus

The project focuses on shallow cumulus clouds, aiming to understand their microphysical composition changes and potential for precipitation. Using CM1 simulations and ParaView visualizations, different thresholds for cloud and rain mixing ratios were explored. The project highlights the importance of thoughtful visualization selection and emphasizes the need to consider

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technical aspects for effective data representation. The simulations demonstrate that cloud cover thinned during heavy precipitation, aligning with previous findings. Overall, the project provides educational insights into shallow cumulus clouds and their evolving composition (see Supplementary Material, Section 1.4, for more details).

4 Conclusions

This publication presents results of a 2-week modeling workshop held at the University of Bonn in 2023. It covered essential topics to run and modify Cloud Model 1 on a high-performance computing cluster, introduced 3D visualization software, and included an introduction to convective storms dynamics. During the second week, students selected their own research questions and documented the skills they acquired in their course reports.

The guided environment provided by an experienced teacher proved to be valuable for the students. After mastering the introductory tasks, students were motivated to explore their own research questions with CM1 and experiment with the visualization tools. This active learning approach fostered intensive work and facilitated a steep learning curve. The use of high-resolution idealized modeling highlighted important aspects of convective processes, such as the complex factors influencing convection initiation, including lift strength, type of lift, and the role of environmental relative humidity and entrainment. Deeper understanding of convective processes significantly helped in data visualization, enabling students to represent phenomena like the helical inflow of a supercell and the vortex generation along gust fronts effectively.

Over time, the participants became increasingly independent. They engaged deeper in their specific research topics and explored multiple ways to visualize their results. In addition, the course teaches useful skills that can be applied in their thesis preparation, graduation phase or in a later professional research career. This additional benefit has also been documented in other disciplines that use active learning strategies in teaching (Wilke, 2003) and is successfully used in atmospheric sciences, too (Handlos et al., 2022; Steeneveld and de Arellano, 2019). In contrast to active learning methods that rely on software designed exclusively for educational purposes (Limbach et al., 2015), the strength of this course lies in its ability to offer students a scientific setting, mirroring the challenges they will face in their future careers. Furthermore, openly accessible (open-source) software is used, encouraging students autonomy in conducting independent research without depending on software solutions that are available at specific institutes only. An analogy to this approach is to provide them with Lego building blocks, enabling the construction of a model car tailored to their particular (research) requirements, rather than providing a pre-assembled vehicle.

With respect to course improvements, a longer time frame for error management would be preferable. Moreover, it would be ideal if the course was accompanied by a lecture on mesoscale dynamics since students could use CM1 to visualize lecture topics, test hypothesis and interpret their data. While the course was initially designed as a block course, it is also adaptable to a weekly lab format throughout the semester. Alternatively, it can be done individually, allowing learners to set their own pace. We recommend this course for anyone interested in studying idealized cloud system dynamics and development. The course material is available at www.orca.nrw (Schielicke, 2023).

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Finally, we would like to conclude the paper with a fazit of two of the participants and co-authors to this paper:

"In this intensive two week course aimed at using the Cloud Model 1 (CM1) for simulating meteorological phenomena and visualizing its data by using ParaView. I found the tools to be incredibly useful, specially the CM1, which offers a wide variety of options for the simulation (from considering different vertical profiles in the atmosphere to different types of earth surfaces that influence the friction). In my case, I simulated a supercell, analyzing the reflectivity and mixing ratios of various hydrometeors within the supercell. This helped me to have a deeper understanding of its development under different initial conditions for this phenomena. The proficiency of CM1 in computing microphysical processes makes it a reliable tool, and integrating its data through ParaView's 3D visualization significantly enhances the comprehension of meteorological interactions." (from Jose Pablo Solano Marchini)

"Simulations are valuable tools for approximating real weather conditions. In this two-week course, we learned from scratch to conduct simulations, exploring idealized cases that shed light on large-eddy simulation principles and modifiable aspects like terrain, warm bubbles, and soundings. [..] A follow-up CM1 course with more intricate simulations, higher resolution, or longer duration could be beneficial. This course serves as an excellent entry point for simulation enthusiasts." (from Yidan Li)

To summarize, the presented CM1 course teaches important skills regarding model setup and simulation and serves as a basic introduction to model code in general, which lays the groundwork for tackling more realistic models, for example WRF, COSMO or ICON. The introduction to 2D and 3D visualization software such as Ncview, ParaView, and VAPOR, complements the learning outcome. The work on projects of the student's own choice further motivates and reinforces the application of learned content.

Code availability. The course contents are available as open educational resource (OER, see Schielicke, 2023). The CM1 source code is available at the CM1 website (Bryan, 2021).

Author contributions. LS planned and structured the paper and designed the course material; AS, JS, JPSM and YL designed their own research projects, generated and visualized the data associated with their subsection, JPSM and YL provided a concluding statement, CG and LS wrote the text of the manuscript and the summaries of the projects based on AS's, JS's, JPSM's, YL's course reports in equal shares. All authors discussed the manuscript continuously to improve the text.

Competing interests. We declare that no competing interests are present.

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