LES Beyond Limits: Storms in Sharp Detail

Large-Eddy Simulations of thunderstorms: Bridging the Gap between Parameterization and Resolution

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In Short

- High-resolution simulations of thunderstorms: The project uses Large-Eddy Simulations (LES) with grid spacings between 6.25 m and 50 m to explicitly resolve storm-scale processes
- From idealized to real-world cases: The research combines controlled simulations of classic thunderstorm scenarios with realistic cases over northern Germany
- Advancing storm modeling across scales: Results will identify the resolution thresholds needed to overcome the convective gray zone

***Figure 1:** 3D-snapshot of an idealized Cumulonimbus at 25 m resolution. The Simulation was conducted by J. Schwenkel, while the image was rendered by H. Knoop with Blender.*

Thunderstorms are among the most intense and locally hazardous weather phenomena in central Europe. They can bring torrential rainfall, flash flooding, hail, and severe wind gusts within very short time spans and over small areas. Despite continuous advances in weather prediction, simulating these events in sufficient detail remains a major scientific and technical challenge. This is largely due to the so-called convective gray zone 1,2—a resolution gap in numerical models where convective processes such as cloud formation, updrafts, and precipitation are only partly resolved, and their subgrid-scale effects must still be approximated through parameterizations.

This project aims to overcome the limitations of the convective gray zone by performing high-resolution Large-Eddy Simulations (LES) of deep convective thunderstorms using the PALM model system. With grid spacings between 6.25 m and 50 m, these simulations are capable of explicitly resolving key storm-scale processes, such as the initiation and development of strong updrafts, the formation of localized precipitation cores, and the generation of cold pools and downbursts. These are all processes that play a critical role in storm dynamics and can lead to localized but high-impact weather extremes—yet they are often missing or misrepresented in coarser operational models.

The project consists of two main phases. In the first phase, we will carry out controlled simulations of idealized convective systems. These include a rotating supercell storm and an isolated cumulonimbus cloud. These setups allow us to systematically investigate how increasing resolution affects the simulation of storm intensity, rainfall distribution, and near-surface wind extremes. By varying the grid spacing and comparing the resulting simulations, we can determine the resolution thresholds at which key features of convective storms—such as downdrafts, gust fronts, or rain shafts—are reliably captured.

In the second phase, the project will move from idealized cases to realistic weather events. We will simulate actual thunderstorms that occurred over northern Germany, a region characterized by relatively flat but topographically structured terrain. These real-case simulations will use PALM's self-nesting capabilities to embed a high-resolution domain (25 m spacing) inside a larger domain (50 m spacing) covering a 120×120 km area. The simulations will be dynamically driven by data from the ICON-D2 weather model, ensuring that the larger-scale weather conditions are realistically represented. The model results will be compared to radar observations and reanalysis data.

From a broader perspective, the project contributes to a growing scientific effort to improve the representation of convective storms in numerical weather. High-resolution LES simulations act as a virtual laboratory, allowing researchers to isolate and analyze processes that are difficult to observe directly in nature. The output generated in this project will provide valuable benchmark datasets for future model development, particularly for so-called Cloud resolving models that aim to bridge the gray zone.

Ultimately, the findings from this project will help answer a key question: What resolution is needed to reliably simulate dangerous storm-scale phenomena? By identifying these thresholds and highlighting the improvements possible with explicit convection modeling, the project supports efforts to produce more accurate and physically grounded weather forecasts. In the context of a changing climate, where extreme weather events are expected to become more frequent and intense, this knowledge is essential not only for scientific advancement but also for societal preparedness and risk reduction.

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More Information

[1] G. Bryan, J.C Wyngaard, and J. Fritsch. Resolution requirements for the simulation of deep moist convection. *Monthly Weather Review.* **131(10)**, 2394–2416 (2003). doi:10.1175/1520-0493(2003)131<2394:RRFTSO>2.0.CO;2

[2] J C Wyngaard. Toward numerical modeling in the “terra incognita”. *Journal of the atmospheric sciences.* **61(14)**, 1816–1826 (2004). doi:10.1175/1520-0469(2004)061<1816:TNMITT>2.0.CO;2

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