Challenges and motivations in developing the ICON atmosphere model

Climate science is based on theory, observations and, also numerical models. Models play an important role because mathematical descriptions thought to describe the climate system cannot be solved analytically but their numerical solution allows one to investigate how different processes may contribute to the climate and climate change. Therefore, numerical models are the first choice at the Max Planck Institute for Meteorology for systematically investigating the key processes of the climate system. Scientists compare the numerical model simulations with observations and examine alternative formulations for selected processes. These include the diverse processes that form and dissolve clouds. Clouds exist on many scales, ranging from small cumulus clouds to deep cumulonimbus, thin cirrus near the tropopause or extensive dense clouds in the lower atmosphere that cover large areas. Each cloud type influences the weather in different ways. This means that the role of clouds within the climate system is complex and represents a great challenge for observations and modeling.

The limited understanding of the interaction of clouds and circulation is an important factor for the uncertainty in climate sensitivity. The climate sensitivity measures the global mean warming of the lower atmosphere following a doubling of the CO_2 concentration compared to the conditions of 1850. As climate sensitivity cannot be measured, it can only be estimated with the help of global climate simulations, making it dependent on the quality of the processes implemented in the models. Parameterized processes, i.e. the formulation of processes that either cannot explicitly be resolved spatially or whose governing equations are not well known, pose a particular problem. Current climate models typically have horizontal resolutions of 100 km and cannot resolve cumulus clouds. Their effects such as vertical mixing of the atmosphere, latent heat, precipitation and radiative effects, must therefore be parameterized based on the resolved environmental conditions, which is subject to uncertainties. The challenge for modeling is to reduce or eliminate such uncertainties. One option is to increase the resolution of global models, so that fewer processes have to be parameterized. In practice, this option is limited by the capability of computer systems and the ability of climate models to make full use of the most advanced computer systems. Alternatively, fine-scale models can be used to explicitly resolve the dynamics of cumulus clouds in a specific region, facilitating a more precise analysis of the processes within this region. A more precise parameterization for global models can then be derived. A model system that is equally suitable for both options is even more advantageous. It allows an investigation of the different temporal and spatial scales within one framework. Toward this end the ICON model system was developed, including components for atmosphere, land and ocean. The atmospheric model, which helps investigating cloud processes, is presented in the paragraph below.

The atmosphere model ICON

The ICON atmosphere model was developed jointly with Germany's National Meteorological Service (Deutscher Wetterdienst, DWD) to create a common tool that is equally suitable for climate research and weather forecasting. The innovations, compared to the previous models (ECHAM at MPI-M and GME at DWD) can be summarized as follows:

- Dynamics: The non-hydrostatic equations of motion allow the simulation of small-scale circulations, such as the strong vertical winds in convective clouds [1]. In contrast, ECHAM and GME were developed based on hydrostatic equations, which are computationally simpler and faster to solve but assume that vertical winds can be accurately derived from the horizontal winds, and thus do not require a vertical wind equation. This simplification in ECHAM and GME is effective for resolutions of ~ 10 km or coarser, but also has a computational advantage in that it requires less communication in massively parallel computations.
- Transport: The transport of trace gases such as water vapor or cloud liquid water is mass conserving. This was not ensured by the numerical methods of ECHAM and GME, so that minor numerical errors could affect budgets of long-lived trace substances, something that is undesirable for long-running climate simulations.
- Parameterized processes: Parameterizations were developed for three applications: climate simulations over decades with resolutions from 40 to 160 km, the numerical weather forecast for about 10 days at a resolution of 13 km, and cloud-resolving simulations over a few days at a resolution of about 100 m. The ECHAM model was exclusively developed for climate simulations, the GME model for weather forecasting.
- Spatial discretization: The unstructured triangular grids allow maximum flexibility in the design of the computational domains. They can cover single regions or the whole globe (**fig. 1**). ECHAM and GME can only cover the whole globe, regional refinements are not possible.
- Numerical efficiency and scalability: An extremely high parallelization of the ICON model was achieved through a partnership with the German Climate Computing Centre (DKRZ), in the context of a BMBF project on high-definintion clouds and precipitation for climate prediction, HD(CP)^2. It enabled the efficient use of the second-largest computer in Europe (Juqueen at Forschungszentrum Jülich) with all 458 752 calculation cores in spring 2015. The old ECHAM model was able to run on at most a few thousand cores.

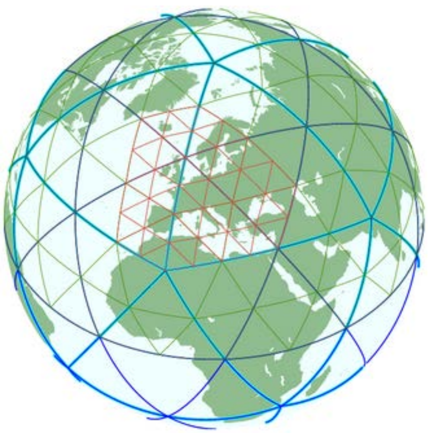

Fig. 1: Example of a twofold refined regional ICON grid. The light blue grid shows the icosahedron defined base grid with 20 triangular faces, 30 edges and 12 vertices. The dark blue grid was created by a first refinement, in which the edge centers form new vertices. The additional grid refinement was only carried out for the northern hemisphere, depicted by the green grid. The red grid shows another refinement step in the region over Europe.

Validation of the cloud-resolving ICON model

In the BMBF-funded project HD(CP)^2, reference calculations for a convective boundary layer with and without cloud formation were carried out for the validation of the ICON model in *large eddy simulations (LES)* with horizontal resolutions of 100 to 25 m. The calculations were also compared with results of specialized LES models [2]. The tests focused on the turbulent boundary layer whose average vertical structure (**fig. 2**), as well as the vertical turbulent transports caused by the vortices, are simulated by the ICON model, similar to the two reference models UCLA and PALM. The uncertainties in calculating the cloud layer (**fig. 2c**), estimated in an earlier model comparison [3], are substantially higher than the differences between ICON, UCLA and PALM.

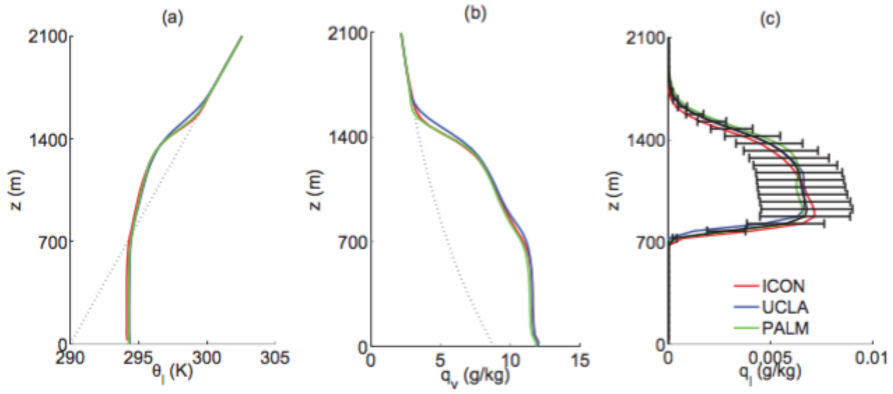

Fig. 2: Mean vertical profiles of (a) wet-potential temperature ϑ_l, (b) the specific humidity q_v, (c) the cloud liquid water content q_l in ICON (red) and the two LES models UCLA (blue) and PALM (green). An uncertainty range for this experiment was shown by Siebesma et al. for the cloud liquid water area in a previous model comparison [3].

First cloud-resolving simulation for Germany

The validated ICON model was used in the HD(CP)^2 project for cloud-resolving simulations over a domain covering whole Germany (**fig. 3**). Simulations were performed for selected days, for which the HOPE observation campaign within the HD(CP)^2 project collected data about the atmospheric structure, clouds and precipitation. In the model, a twofold refined regional grid with a total of 32 million grid cells and 150 layers was developed. The base grid, with a resolution of 600 m, obtains the boundary conditions from archived forecasts that DWD calculated with the regional COSMO-DE model at a resolution of 2.8 km. In the ICON model, this data was interpolated and integrated by nesting on the slightly smaller second and third grid with 300 and 150 m resolution. An animation performed by colleagues at the DKRZ visualizes the second grid and shows a storm system moving over Germany on 24 April 2012.

A more quantiative evaluation of the regional version of ICON is presented in Figure 4, which shows the temporal development of the boundary layer height around Jülich on 24 April 2013, with observational data of the lidar instruments HALO (JOY) (wind lidar) and POLLY (LAC) (aerosol lidar) and radiosondes (RS (KIT)) as well as data from three models: ICON (ICON-LES (HOPE)), PALM (PALM) running with simplified boundary conditions, and COSMO-DE (COSMO), from which the boundary conditions for ICON originate. Since the aerosol layers decouple from the boundary layer at night, the two lidar measurements agree only during the day. Especially in the afternoon, the radiosonde measurements show a higher altitude of the boundary layer than the lidar measurements. All three models demonstrate a good accordance with observational data between 9 and 15 UTC, while the ICON simulation is closest to the wind lidar data. There are, however, differences in the formation and disintegration of the boundary layer between 6 and 9 UTC and 15 and 18 UTC, respectively. Only ICON shows the rapid formation and disintegration as shown in the high temporal resolution wind lidar measurements. Hence, these first realistic simulations are promising for further investigations of the implemented observations and ICON simulations in the HD(CP)^2 project.

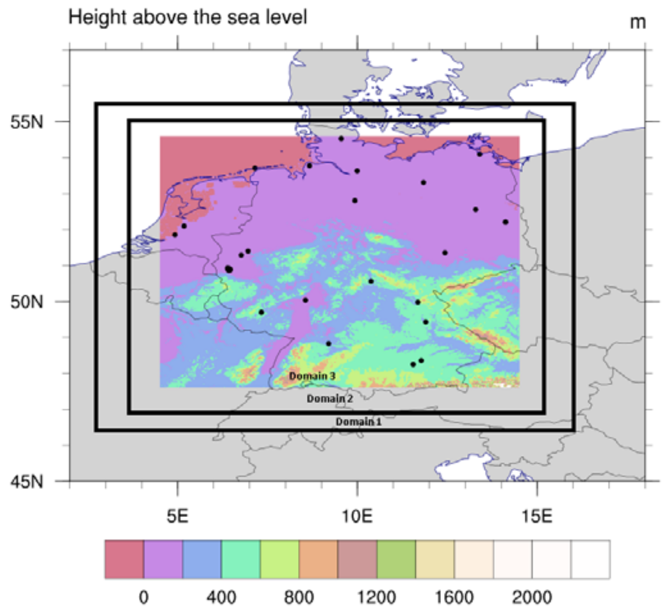

Fig. 3: Computational domains of the Germany simulations within the HD(CP)^2 project: In "Domain 1", with a resolution of 600 m, the model obtains the temporally and spatially interpolated boundary conditions from archived regional forecasts of the COSMO-DE regional model by DWD. "Domain 2" and "Domain 3" - with representations of the surface elevation in [m] – run with resolutions of 300 and 150 m and are connected by a nesting with "Domain 1" and "Domain 2", respectively. The main simulation is carried out in "Domain 3".

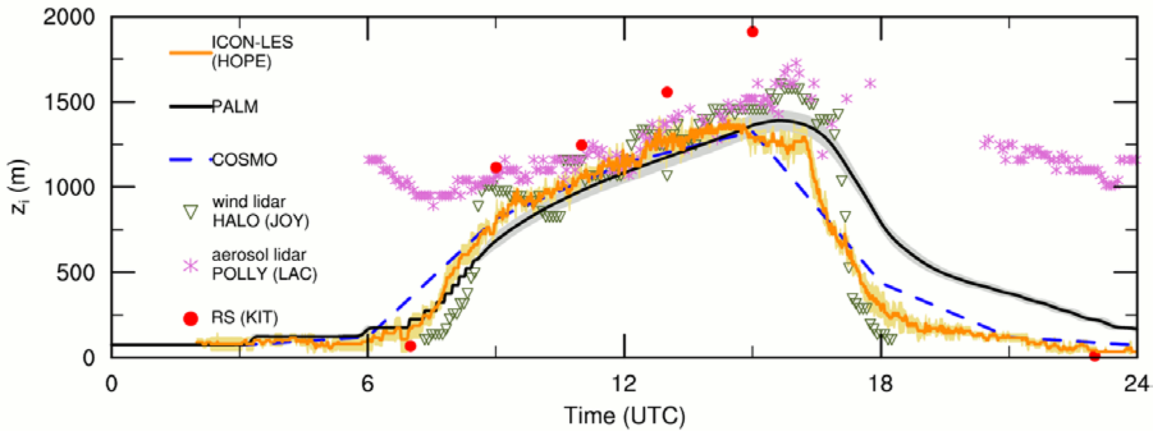

Fig. 4: Temporal progression of the boundary layer depth on 24 April 2013 in lidar and radiosonde measurements and in the Germany-wide ICON simulations (orange). The boundary layer height is shown additionally in the weather forecast model COSMO-DE (blue) and in an idealized simulation with PALM in a smaller area at a resolution of 50 m.

Summary

The ICON atmosphere model is a new and unique model that allows the simulation of atmospheric circulations on the largest supercomputers on the scale of 100 m to the planetary scale due to the equations, discretization methods and software structure. It can also be coupled with an ocean model, turning it into an Earth system model. This opens up new horizons for the direct examination of the role of even small clouds in the climate system, with the possibility to further investigate the uncertainties of climate sensitivity. In the course of the first application within the HD(CP)^2 project, Germany-wide cloud-resolving simulations were carried out and were successfully compared to new observations for the first time.

References

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