Multi-scale WRF simulations for atmospheric process understanding and boundary layer research

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A multi-scale configuration of the Weather Research and Forecasting (WRF) model, containing 4 nests from 2.7 km down to 100 m horizontal resolution, is applied to investigate the evolution of turbulence on a sunny spring day in Western Germany. The simulations are driven by realistic lower boundary conditions for orography, land use and soil characteristics. The initial and lateral forcing of the meteorology is done with the operational analysis of the European Centre for Medium-range Weather Forecasting (ECMWF). The selected case is an intensive observation period during the HD(CP)2 Observation Prototype Experiment (HOPE) where also lidar systems of the Institute of Physics and Meteorology were operated. The evolution of turbulence during the day in the fine-scale 100 m domain is presented on the Symposium.

1 Introduction

Numerical models are excellent tools for process studies, since they provide a full 4D representation of the atmosphere. Having said that, commonly-used mesoscale models do not permit the explicit simulation of smaller-scale processes such as large turbulent eddies (100-2000 m) since the whole turbulence spectrum is parameterized (or inferred non-explicitly). In order to 'see' smaller circulations, so-called "Large-Eddy-Simulation" (LES) models can be used. Through application of extremely high resolution and low-pass filtering, we directly simulate larger eddies – the dominant spectra for turbulent transport of heat and moisture.

For a long time, LES models were applied to investigate turbulence under 'idealized' land surface (homogeneous) and lateral boundary (periodic) conditions (e.g. [2],[1]). The natural progression is to apply LES models within 'real' conditions. Then we can simulate the diurnal evolution of turbulence above actual landscapes and under different meteorological conditions. Such representations are crucial given the 2-way coupling between the land surface and the atmosphere, known as land surface-atmosphere (LSA) feedbacks. Real-case simulations also allow us to make comparisons against field observations to assess the model performance.

2 Methodology

For all tasks, the Weather Research and Forecasting advanced research model (WRF-ARW) (in the following abbreviated as WRF) [4] is applied. WRF is a state-of-the-art numerical weather prediction model designed for both research and operational applications. It is suitable for a broad span of applications across scales ranging from global down to fine large-eddy scales as used in this presentation. WRF is applied in a multi-domain configuration starting with a resolution of 2.7 km in the outer domain. Three more nests were inserted with resolutions of 900 m, 300 m and finally 100 m. Figure 1 shows the domain configuration of the experiment.

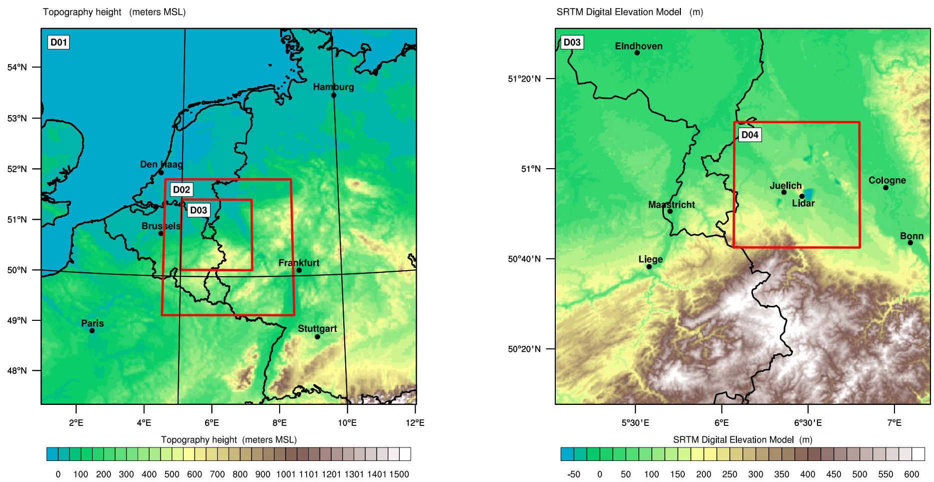

Figure 1: Domain configuration of the WRF model chain. Left: Outer three domains with 2700 m resolution (D01), 900 m resolution (D02) and 300 m resolution (D03). Right: Location of the innermost domain with 100 m resolution (D04) within D03.

All domains are simulated simultaneously in a one-way nested mode. The outer domain was driven by the ECMWF operational analysis to initialize the meteorology for the case study as well as possible.

The model physics is represented by a well-tested set of parameterizations capable to represent atmospheric processes over the range of the selected scales. It is furthermore coupled with the NOAH-MP land surface model [3] to realistically simulate the land surface and its interaction with the lowermost atmosphere. Operating WRF in LES mode requires both a high horizontal and vertical grid resolution. Both need to be of the same size over the vertical range of the investigated processes. Since we investigate processes from the boundary layer up to the full troposphere, more than 100 vertical levels are necessary.

Important first task was the optimization of the setup. For this purpose, a series of sensitivity experiments for a fair weather spring day in 2013 was carried out. In the following, the results of the final configuration for this case are discussed.

3 Preliminary Results

With the optimal setup, the evolution of the convective boundary layer at that day was investigated. Figure 2 shows four time steps during the evolution of the boundary layer. Shown is the turbulent kinetic energy, illustrating the intensity of turbulence, at model level 19 (approx. 1000 m above ground).

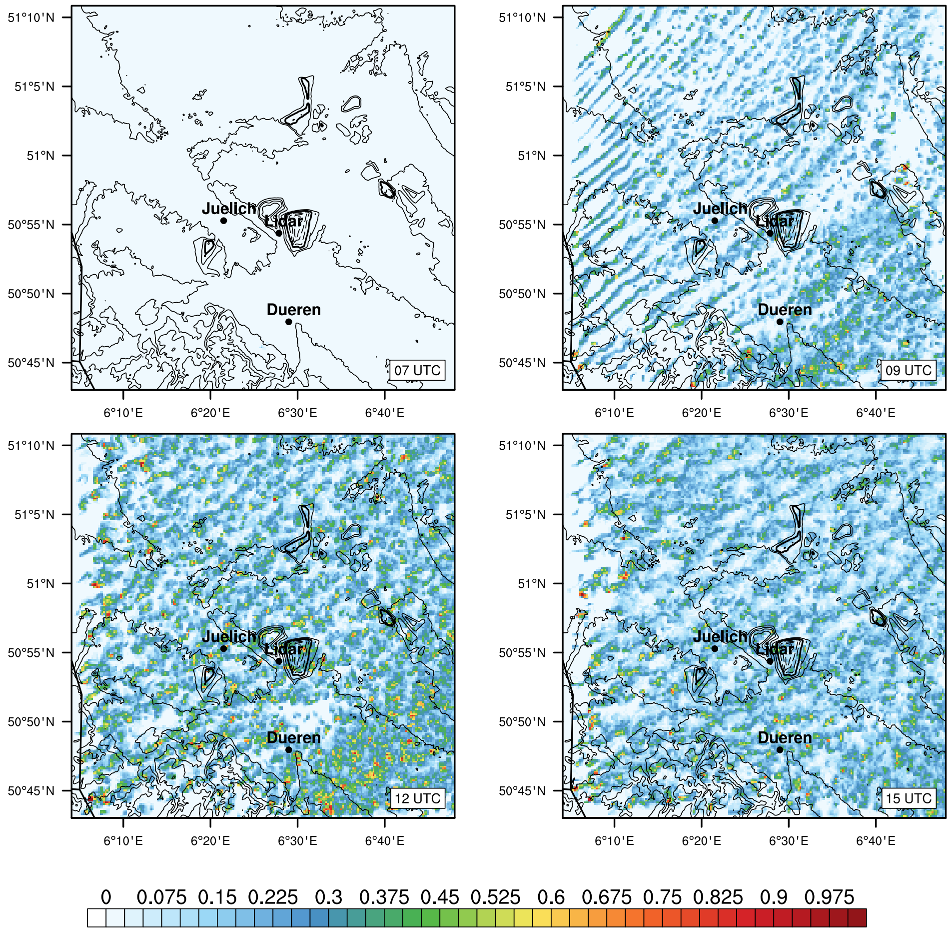

Figure 2: Turbulent kinetic energy (cm^2/s^2) for model level 19 (approx. 1000 m above ground) simulated by WRF with 100 m horizontal resolution at 07 UTC, 09 UTC, 12 UTC and 15 UTC, 24 April 2013.

At 7 UTC, before the onset of turbulence, the values are small. At 9 UTC, turbulence slowly starts to develop. Since the turbulent eddies are still weak and small, the strip-like structure influences a large part of the model domain. Such role-like structures are typical for environments with weak turbulence , as shown by [5]. Strongest turbulence occurs in the southeastern part of the domain where the break-up into turbulent eddies already occurred supported by the westerly flow over the higher terrain to the west. At 12 UTC, the convective boundary layer is fully evolved. Only a narrow region on the windward side of the domain is seen where the adjustment from the coarser outer domain takes place. At 15 UTC, turbulence already weakened. Interestingly, the horizontal dimension of the turbulence elements seems to be larger comparing 12 and 15 UTC. This is consistent with the daytime growth of the turbulent eddies. The narrow region of weak turbulence along the windward boundary indicates that the transition from the coarser 300 m domain to the inner 100 m domain works smoothly and no artificial circulations are induced.

Furthermore, time-height cross sections of different variables, demonstrating the temporal evolution of the boundary layer, were investigated and shown in Figure 3. It covers the time period from 10 UTC to 16 UTC and nicely illustrates the evolution of the boundary layer. The temporal resolution of the data is 5 minutes.

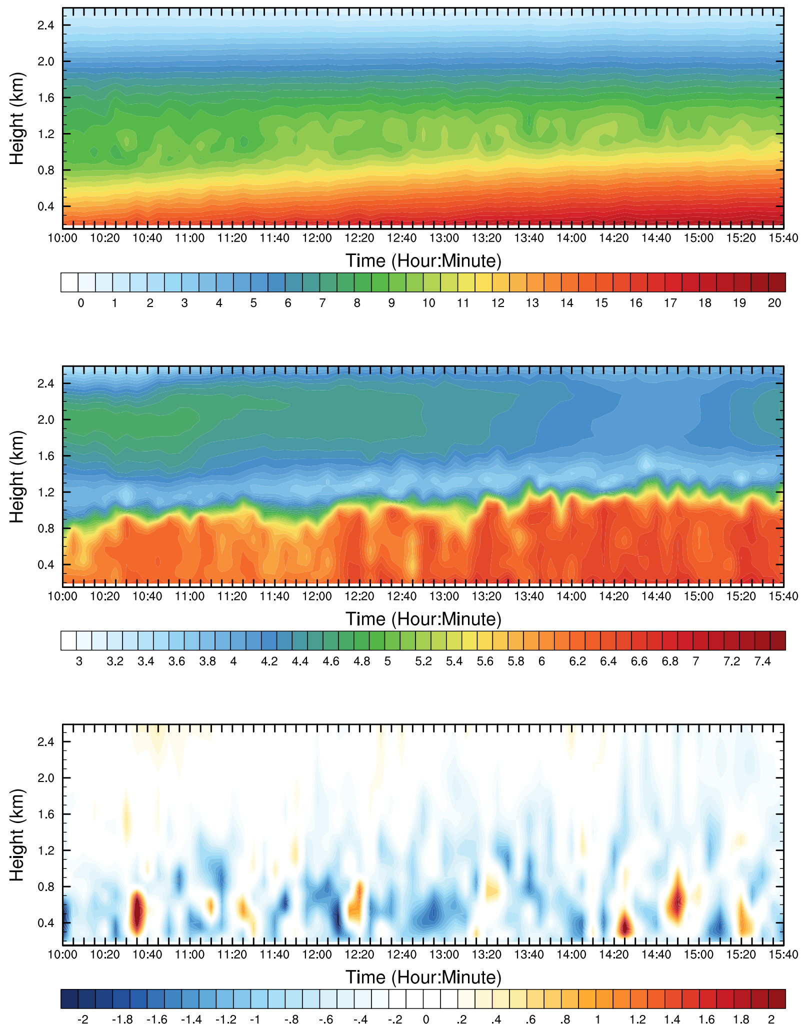

Figure 3: Time-height cross sections of the lower 2.6 km of the model atmosphere at the location of the Hohenheim lidar systems for 24 April 2013. Top: Temperature (°C). Middle: Water vapor mixing ratio (g/kg). Bottom: Vertical velocity (m/s). Output interval of WRF was 5 minutes.

In the temperature panel (top), the rise of the boundary layer top height during the development is nicely seen. Furthermore, the iterating upward transports of warm air and downward intrusions of colder air into the boundary layer are seen. The boundary layer top and the vertical transports are even better seen in the water vapor cross section. The sharp gradient in the water vapor field marks the boundary layer top. The dry layer directly above the boundary layer top and an elevated moister layer above, a precursor of an approaching low pressure system from the west that lead to cloudy and rainy conditions during the following two days are well represented. Iterating moist and dry regions mark rising moist bubbles and the downward intrusion of dry air from above the boundary layer top. The vertical velocity panel (bottom) shows active turbulence by iterating upward and downward motion. As expected from observations, narrow and strong updrafts iterated with broader and weaker compensating downdrafts.

4 Conclusions and outlook

The first results are very promising. Turbulence evolves as expected from literature and no obvious problems caused by the downscaling from mesoscale to LES are seen. This indicates that the applied setup is a feasible tool for the investigation of turbulence under realistic case-study-based conditions. The system will be further optimized in future applications during upcoming field campaigns and the investigations of the process evolution during high-impact weather events (e.g. severe convection).

References

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