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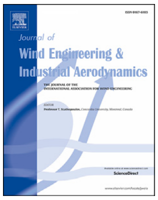

Model comparison of two different non-hydrostatic formulations for the Navier-Stokes equations simulating wind flow in complex terrain

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ABSTRACT

An anelastic model and a quasi-compressible model for the simulation of wind flow in complex terrain are presented. The models are based on the Reynolds Averaged Navier-Stokes (RANS) equations in combination with the k-ε turbulence model. Additional terms are implemented in the transport equations to describe stratification of the atmosphere to account for the Coriolis forces driven by the Earth's rotation, as well as for the drag-forces and turbulence production and dissipation due to different types of land use.

The modelling approaches are verified by means of academic test cases assessing effects of the Earth's rotation, density driven flow and canopy. The validation of the models is performed by investigating a wind test site near Geislingen a. d. Steige in Southern Germany. Fife hole probe velocity measurements using MASC systems (unmanned small research aircraft UAV) at different locations are compared with the simulation results for the main wind regime. Therefore, the orography and flora of the Earth's surface are described by high-resolution digital data from State Authorities for Spatial Information and Rural Development Baden-Württemberg (LGL). Boundary and initial conditions are based on mesoscale simulation data from the COSMO-DE weather model of the German Meteorological Service (DWD).

1. Introduction

Wind energy plays an important role in the renewable electricity supply of Germany. In 2015, according to the Federal Ministry of Economic Affairs and Energy, 42.3% of the renewables-based electricity generation came from on-land and offshore wind energy, yielding a total power generation of 79.2 bn kWh. Most of the wind turbines are located on flat terrain or in coastal regions. Alternately, wind energy production in Southern Germany, with its widely hilly or even mountainous and forested landscape, has become more and more of an issue. The local electric power generation reduces transmission losses and the effort needed to build up the transmission infrastructure. However, finding appropriate sites with sufficient wind potential and an acceptable orography-induced turbulence level, especially in this densely populated territory, is a challenging task. Wind atlases may often give a first indication of the wind potential. Unfortunately, in many cases, their resolution is insufficient. Meteorological observation data are rarely available at possible wind turbine locations in these areas. An interpolation of the local wind situation based on the nearby observation data may lead to poor correlation or even misleading information. Instrumental tower measurements are very expensive and limited in height. It is often not feasible to extrapolate the measured flow field in complex terrain with increasing height because the boundary layer is not fully developed. Alternately, roughly resolved wind fields from Numerical Weather Prediction (NWP) models are not directly suitable for the prediction of wind potential because of their limited horizontal spatial resolution of approximately 1.0 km. Non-hydrostatic numerical weather prediction (NWP) and high-resolution mesoscale models have been applied to, for example, simulate in detail the temporal and spatial behaviour in the Swiss Rhine Valley (Jaubert et al., 2005; Zängl et al., 2004). Due to the limited resolution of the model grid, the vertical extent of hills was systematically underestimated in these numerical simulations (Beffrey et al., 2004), and as a result, the flow field, with its specific flow feature characteristic for complex terrain, can only be resolved to a certain extent.

With continuously increasing computer power and decreasing hardware cost, CFD simulations based on Reynolds Averaged Navier-Stokes (RANS) equations or even detached-eddy simulations (DES) and large-eddy simulations (LES) for wind flow in complex alpine terrain have become a feasible option. Looking at mountainous landscapes, CFD

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simulations of wind flow already provide valuable information to answer various questions. It is used for the calculation of wind load on buildings (Tominaga et al., 2008), even in alpine regions (Plüss and Menti, 2008), and enables prediction of the transport of airborne substances (Aliabadi et al., 2006). In addition, for the numerical simulation of wind flow, these methods are becoming more and more attractive with the increasing power of computers (Montavon, 1998; Michioka and Chow, 2008; Maurizi et al., 1998). Even the simulation of wind farms including the representation of turbine blades has been approached (Lee et al., 2009; Montavon et al., 2009). Additionally, models are used for reliable wind farm operational assessment in complex terrain (Castellani et al., 2015). Lately, the interaction of complex terrain with the wakes of wind turbines is increasingly investigated using different two-equation turbulence models (Politis et al., 2012) and more recently LES (Berg et al., 2017). The boundary data for these simulations are typically introduced from observation station measurements. Alternatively, they are generated assuming a flow direction and mean velocity in combination with the assumption of a fully developed boundary layer (Schulz et al., 2016). However, this simplification in complex terrain is hardly valid.

Data from weather models can also be used as boundary conditions for the CFD models, offering the opportunity to get more realistic boundary conditions. For example, in (Veiga Rodrigues et al., 2016; Knaus and Dürr, 2015), one-way coupled simulation methods based on RANS are shown, where the boundary conditions are supplied from WRF and COSMO-2 models, respectively. Despite the comparably low spatial resolution of the weather forecast models, this seems to be the most promising approach. Further validation of this coupled simulation is mandatory to obtain a broader understanding of the expectable accuracy for different situations of land use, topography, and stratification of atmosphere and wind regimes. LES and DES promises higher accuracy of the simulation results than simulations using RANS. However, the response time even on massively parallel supercomputers is still extremely high. RANS offers a good compromise between run time and accuracy and therefore is more appropriate for operational model application in terms of micrositing.

In the forested areas, the model has to be adjusted to get a good representation of additional drag forces and the generation and dissipation of turbulence. An overview of the flow and turbulence phenomena is given by Finnigan (2000). Two main approaches have been developed and successfully applied in the past. One way is to introduce a displacement length z_0 in the logarithmic wall function (Brutsaert, 1982). Another possibility is the use of canopy models, introducing source terms in the momentum and turbulence equations as first suggested by Svensson and Häggkvist (1990). Similar approaches have been adopted by Liu et al. (1996) and Green (1992). Shaw and Schumann (1992) set up a test case of a forested area for the verification of these canopy models. Silva Lopes et al. (2013) compared the different approaches using the data of Shaw and Schumann and devised a further canopy model. However, these models are developed and validated by means of academic test cases or for flat terrain. Therefore, further validation for complex terrain is advisable.

Stratification of the atmosphere is mostly modelled using an anelastic formulation of the Navier-Stokes equation based on the Boussinesq approximation. This leads to a formulation for the transport equations using a hydrostatic reference state and the potential temperature. Montavon (1998) used this approach for the simulation of wind flow. Kristof et al. (2009) and Schneiderbauer and Pirker (2010) suggested a quasi-compressible formulation using a source term in the transport equation for the potential temperature. However, the use of a source term in the temperature transport equation is also feasible (Knaus and Dürr, 2015), giving a formulation of the energy transport equation that is as close as possible to the formulation in standard CFD codes.

Main objective of this paper is to achieve a validated simulation model with acceptable response time for the operational use in terms of micrositing and planning of measurement campaigns in complex terrain. The implementations of two different numerical non-hydrostatic formulations, anelastic and quasi-compressible, of the Navier-Stokes equations in the commercial CFD code ANSYS CFX are described and compared. The energy transport is based on the potential temperature and temperature. Boundary data for the initialization of the wind field are taken form the weather model COSMO-DE of the German Meteorological Service (DWD). Orography and land use are described with the aid of digital information from State Authorities for Spatial Information and Rural Development (LGL). The models are compared for verification by means of three different academic test cases investigating Coriolis forces, the stratification of the atmosphere and land use. The impact of different land use is addressed by comparing four different canopy models, as well as the simplest approach of using a displacement length in the logarithmic law of the wall. Finally, investigations for the validation of the models by means of measurement data were carried out. Therefore, exemplary for an area around Geislingen a.d. Steige near Stuttgart, Southern Germany was chosen. There, the wind test field of the research cluster WindForS is located. The topography is characterized by an escarpment, and the ground is partly forested. Extensive measurement campaigns using various measuring technologies have been conducted within the research projects Lidar Complex and KonTest funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) in the timeframes 2012–2016 and 2013–2015, respectively. Especially the measurement data from unmanned aerial vehicle (UAV) is perfectly suited for the model validation, covering a large part of the test site investigated (Wildmann et al., 2014b). In future further measurement campaigns and simulations are planned, characterizing the flow conditions in detail for the test site. Additionally, two 0.75 MW wind turbines will be installed in the BMWi project WINSENT, enabling widespread and profound investigations for the use of wind energy in complex terrain. The work presented in this paper delivers substantial information for the micrositing of the test site, especially to find the most appropriate positions of the wind turbines and the measuring masts, as well as for the definition of measurement campaigns using Lidar and UAV.

One important task of the research project WINSENT is to build up a coupled simulation process enabling the prediction of wind flow in complex terrain on all relevant time and length scales. The process will integrate the meso-scale predictions of the weather forecast model, the CFD models for micrositing, as well as, in time and space, highly resolved CFD models for the simulation of the flow around the blades, including fluid-structure interaction. The work described in the publication is an essential part of this model chain.

2. Physical model

The computational method is implemented in the commercial software ANSYS CFX Version 17.0 (ANSYS 2016) based on the finite volume approach. The continuity equation, the Reynolds averaged momentum equation and the energy equation, as well as two transport equations for the k-ε turbulence model, are solved. The SIMPLEC method (Doormaal and Raithby, 1984) is applied to compute pressure. The pressure-weighted interpolation method (PWIN) (Rhie and Chow, 1983) is used to prevent the decoupling of velocities and pressure on the non-staggered grid. The convective fluxes are approximated for all transport equations with a bounded second-order upwind scheme.

Two different formulations for momentum and energy equations are compared. Therefore, an “anelastic” formulation and a “quasi-compressible” formulation are set up as described in the following chapters. Quasi-compressible means, according to Straka et al. (1993), that density is only dependent on temperature and not on the flow velocity. This assumption is appropriate for low-Mach-number flows as found in the atmospheric boundary layer. Additional terms were implemented to incorporate Coriolis forces and terms to account for the stratification of the atmosphere. Furthermore, the capabilities of the software are extended to capture the influence of different land use on drag forces, as well as turbulence production and dissipation.