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Measuring the local wind field at an escarpment using small remotely-piloted aircraft

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ABSTRACT

A remotely-piloted aircraft (RPA) is used in this study to collect high resolution data of the flow in complex terrain at a potential site for a wind energy test field in Southern Germany. It is described how such a system was used to retrieve information about the flow field, turbulence intensity, vertical wind components and shear at an escarpment site that is known for its high wind potential. Measurements were done with the aircraft on several days with varying wind and weather conditions, while the focus of the study is on the characterisation of the flow field in main wind direction and neutral stratification. It is shown that flow inclination of up to 30° is found over the escarpment, but attenuates within a few hundred metres downstream. The formation of a reattached boundary layer could be measured, as well as an increased turbulence intensity in the reattachment zone. The results are highly valuable information for the planning of a wind energy test site at the location of the experiment and can also be used for the validation of numerical simulations and remote sensing instruments.

1. Introduction

The German government has made sustainable energy a high priority social task in the 21st century, and this requires high-efficiency renewable energy technologies which can compete economically with nuclear and fossil-fuel energy resources. Wind energy is of primary importance for renewable electricity generation and large investments are being made in the field. Without considering political and social aspects of wind farm siting, recent studies show that large wind potential does not only exist offshore, but also onshore, and even in the Southern federal states of Germany [1]. Generating energy close to the consumer reduces the necessity to strengthen the electric-line system. In the federal state of Baden-Württemberg, the best potential sites for wind energy are found in complex terrain, i.e. in the Black Forest, or the Swabian Alb. While the wind flow over simple geometries like a forward-facing step [2,3], or a sine-shaped hill [4] can be modelled and mathematically described, wind flow in complex terrain is not well understood, and it is not easy to model or predict without the help of advanced computational fluid dynamics (CFD) simulations. Even though these simulations are advanced tools that can even resolve turbulence to a certain degree with the help of large-eddy simulation (LES), an initialisation and validation of the results is essential. Rokenes and Krogstad [5] have done an extensive wind tunnel study about the flow over a generic model of the mountainous terrain at the Norwegian coastline and were able to show flow speed-up, flow separation and turbulence distribution for different scenarios. So far, validation of these kind of experiments in the real world has not been possible with an adequate level of detail to verify the simulations and wind tunnel experiments. Common practice to measure the wind flow that the turbine experiences with a single upstream meteorological tower is insufficient for a wind flow that is horizontally heterogeneous and strongly depending on the wind direction. Lidar instruments, that have become increasingly popular for wind-energy research have weaknesses in complex terrain, because they assume a homogeneous wind field and a negligible vertical wind component [6]. Only recently, methods to retrieve the three-dimensional wind vector from lidar data have become popular in wind-energy research, but they require a high investment in at least three synchronously scanning instruments and provide a spatial average of several tens of meters [7–9]. A promising tool to investigate small-scale inhomogeneities and processes in the atmospheric boundary layer (ABL) are remotely-piloted aircraft (RPA), also known as unmanned aerial vehicles (UAV). Using these platforms as sensor

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carrier for fast-response thermodynamic sensors, it is possible to acquire atmospheric data with sub-meter resolution, covering areas up to one square kilometer in all heights relevant to wind energy and boundary-layer meteorology in general [10–13]. The high spatial resolution even allows to investigate and quantify small-scale turbulence, which is increasingly in the focus of turbine-load research [14]. In several projects, the possibility to use RPAs for wind-energy research has already been explored. The studies by Giebel et al. [15], Reuder et al. [16], Subramanian et al. [17] and Wildmann et al. [12] did all use RPA to evaluate the possibilities to study inflow and wake of wind turbines. In the framework of the projects KonTest and Lidar Complex, initiated by the research initiative WindForS (www.windfors.de), a RPA was applied to investigate the wind flow over an escarpment in the Swabian Alb. The data that was collected on more than ten experiment days gives valuable insight into the flow distortion that is caused by the escarpment and the effects downstream, at a site that is currently considered for the installation of a wind energy test field.

2. Experiment description

The focus of this work is on studying the flow at a potential wind energy test site in complex terrain using in-situ measurements from a RPA. In this section, the location of the experiment, and the meteorological instruments that were used during the experiment are described in detail.

2.1. Location

The location that was chosen for the experiment and is also considered for a wind energy test site is located along the so-called 'Albtrauf', a long stretched mountain ridge in the Swabian Alb in Southern Germany. The main feature of the site is an escarpment of 270 m height with respect to the valley. The first 100 m from the top are characterized by a very steep slope of up to 40° and are almost fully covered with forest. Further West, the escarpment smooths out into a more gentle slope of heterogeneous land-use down into the river valley. The edge of the Albtrauf is not straight, but curved in a complex shape. At the location of the test site, the wind direction normal to the crest is approximately 300° (compare Fig. 1). Since considerably higher average wind speeds are found on top of the escarpment with respect to the valley, the site already features nine wind energy converters (WEC), which makes it one of the largest wind farms in the federal state of Baden-Württemberg. All of the already present WECs are placed with more than 1 km distance to the escarpment. The focus of the measurements in this experiment are in closer proximity, over the crest, and upstream the escarpment, in order to get a full picture of the flow distortion. What makes the site particularly interesting for wind-energy research is the fact that the main wind direction is West-North-West (see Fig. 1), which is perpendicular to the escarpment. There are some considerable orographic features upstream the escarpment, which could have an influence on the wind flow depending on the incoming wind direction within a very narrow angular band. Fig. 2 shows the terrain profile in three different directions.

2.2. Instruments

While the focus of this work is on the analysis of measurements by an RPA, there are more instruments installed on site, which could also be used to gain auxiliary information about the meteorological conditions on some of the campaign days and will be increasingly used in future campaigns. Table 1 gives an overview of all flight days, and the auxiliary measurements that were available. Flight days that were not considered for further analysis in this study, because the main wind direction was not met, or the wind speeds were too low, are shaded gray.

2.2.1. Multipurpose airborne sensor carrier

The multipurpose airborne sensor carrier (MASC, see Fig. 3), which has been operated by the University of Tübingen since 2012, is a fixed wing remotely piloted aircraft with wing-spans from 2.60

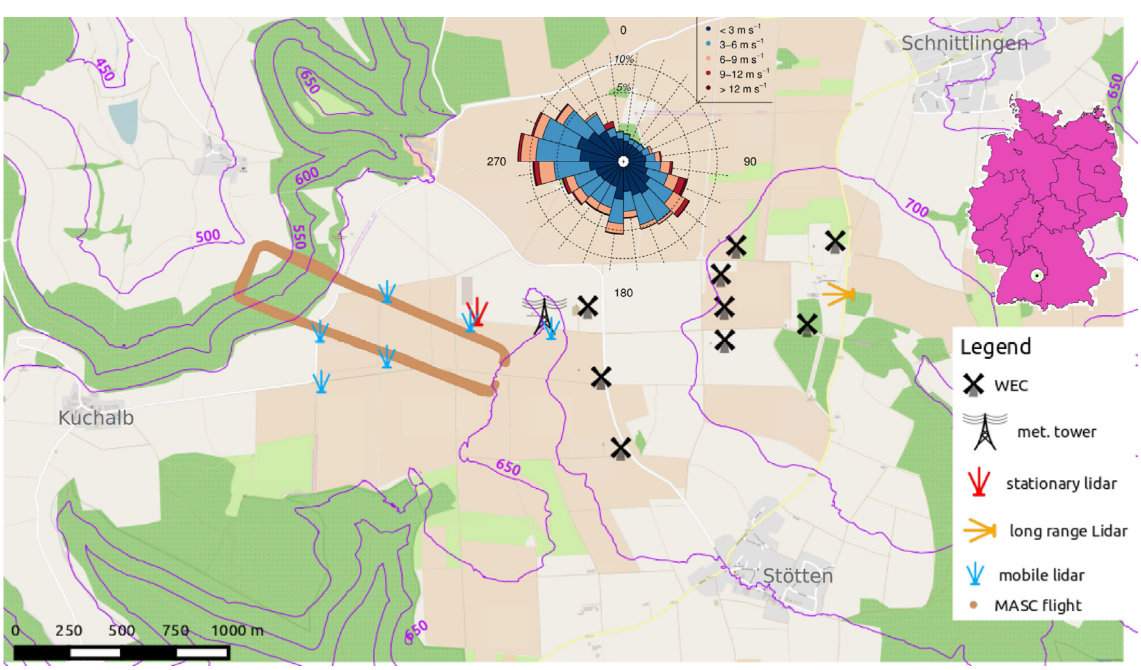

Fig. 1. Overview of the measurement site at the Swabian Alb. The wind rose was generated from cup anemometer measurements at 100 m at the meteorological tower from December 2011 until February 2013. The location of the test site in Germany is visualized above the legend on the right. Background map layer: Data CC-by-SA by OpenStreetMap.