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RESEARCH ARTICLE

REVISED Resolving three-dimensional wind velocity fields in complex terrain using sequential wind-Doppler LiDAR, CFD and wind turbine measurements - Gotthard Pass, Switzerland

[version 3; peer review: 3 approved, 2 not approved]
Previously titled: "Resolving three-dimensional wind velocity fields with sequential wind-Doppler LiDAR, for wind energy in the complex terrain - Gotthard Pass, Switzerland

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Abstract

Background Understanding the effects of complex terrain on wind turbines in alpine regions requires high-resolution computational modelling accompanied by detailed wind observations. In technologically advanced measurement campaigns, often multiple synchronised wind-Doppler LiDARs are deployed to overcome the limitation of these instruments to only measure line-of-sight velocity. Methods In this work, a novel deployment method, a sequential wind-Doppler LiDAR deployment is introduced. We present the example of a field campaign on the Gotthard Pass, a narrow north-south permutated high-mountain pass in the central Swiss Alps. We propose a matching algorithm that can robustly group wind profiles, enabling comparable scientific detail to study turbine efficiency as in synchronised triple LiDAR campaigns, whilst only requiring a single LiDAR instrument to be deployed. Results In the three-month study period in the summer of 2023, we successfully used turbulence kinetic energy, wind shear and veer, as well as wind channelling to explain turbine power production discrepancies observed in the five turbines erected on a mountain pass.

Plain Language Summary

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We have developed a new method of using an existing measurement device to improve the information we can gather about the changes in the wind as they pass over a mountain pass. Five wind turbines were constructed in 2020 on top of a prominent Swiss mountain pass in the Gotthard Wind Park. It is known that these mountain winds are much stronger due to an effect called wind channelling, allowing the wind turbines to generate more energy. With our new measurement method, we can visualise the airflow through the wind park with just one sensor by applying an algorithm that can identify similar wind conditions at different times. Our measurement campaign during the Summer of 2023 allowed us to study several different flow patterns and identify some complex flow structures that affect the efficiency of the wind turbine. We show for each turbine, specifically for Northerly and Southerly winds, how efficient their energy production is, and explain with our detailed wind flow measurements, how these can arise due to the surrounding mountains.

Keywords
wind, energy, complex terrain, lidar, wind turbine, shear, turbulence, turbulence kinetic energy, wind turbine efficiency, wind channeling, stratification, atmosphere, Gotthard, Switzerland

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REVISED **Amendments from Version 2**

In response to reviewer comments, we have revised the manuscript to improve clarity, methodological transparency, and scope definition. First, the title has been updated to explicitly reflect the combined methodology, acknowledging that the reconstruction of three-dimensional wind fields relies on sequential wind-Doppler LiDAR, CFD simulations, and wind turbine measurements, rather than LiDAR alone.

In the Results section ("Wind shear and veer"), we added a new paragraph explicitly referencing the classical Ekman/Coriolis framework as the baseline expectation for vertical wind veering in the planetary boundary layer. This clarifies that the observed wind-direction changes at L8 deviate from Ekman theory due to dominant local topographic forcing.

Several methodological limitations are now more clearly acknowledged in the main text. In particular, we emphasize that the turbines and LiDAR transect are located along a topographically channelized plateau, where flow complexity is reduced compared to exposed ridges. We explicitly note that flow inclination and separation in more complex terrain may violate the horizontal homogeneity assumption required for ground-based Doppler LiDAR retrievals. We further clarify that the HiCAR v1.1 model resolution (50 m) does not resolve sub-grid variability at LiDAR beam scales, and therefore cannot be used to visually demonstrate horizontal flow homogeneity.

The figures, especially composite Figures 14 and 15, have been reprocessed and pre-typeset as single high-DPI figures to address quality issues. We also corrected some small language and terminology issues throughout the manuscript.

Finally, the Conclusion has been refined to clearly state that the proposed approach is most applicable to channelized flow conditions within complex terrain, while explicitly acknowledging reduced applicability at exposed hilltops and ridges.

Any further responses from the reviewers can be found at the end of the article

Introduction

Exact and reliable measurements of the three-dimensional wind are paramount for wind energy potential calculations used to design wind farms. Wind measurements in complex terrain are much more challenging than over flat terrain due to the increased complexity of wind patterns both horizontally and vertically. Complex terrain, in a wind energy assessment (WEA) context, refers to an area with varied and intricate orographical features that can significantly impact wind flow patterns. Complex terrain often includes diverse landscape elements such as hills, valleys, ridges, cliffs, boulders, trees, or human infrastructure irregularities such as buildings or wind turbines that can cause complex interactions with the incident wind.[1] In WEA, understanding and quantifying the effects of complex terrain is crucial because these features can lead to variations in wind speed, wind direction, and turbulence, influencing the performance of the wind turbine by the non-idealised wind flow into the turbine.[2]

In Switzerland, the consideration of complex terrain for WEA is particularly pertinent. Policymakers have shown their intentions to phase out nuclear energy sources and transition to a fully renewable energy strategy by 2050,[3] which was approved by the public referendum on 21 May 2017. In a 2022 report by the Swiss Federal Office of Energy, it was concluded that nearly half of Swiss wind energy potential is located in the alpine region.[4] This amount becomes even more impressive when the issues related to alpine wind energy are highlighted: 1) the logistics of wind turbine construction in the mountains is more challenging and costly,[5,6] 2) the endangerment of wildlife, and especially bird species can be unacceptable in some regions,[7] 3) social acceptance in the form of nature and wilderness zoning, including natural horizon objections can limit wind turbine projects to several kilometres away from settlements and mountain roads or trails.[6,8] The recent construction of several wind parks in the complex terrain of the Alps emphasises the imperative for further detailed studies in this domain. The present study focuses only on the physical aspects of wind potential assessment, not on ecological and social acceptance issues.

LiDAR studies in complex terrain

Several extensive field experiments addressing flows in complex terrain have been conducted in the past twenty years. In 2007–2008, the Bolund experiment, ~25 km East of Copenhagen, Denmark, set the benchmark for experimental complex terrain studies using remote sensing applications such as wind-Doppler Light Detection and Ranging (LiDAR). This small 300 m wide mesa-shaped island with slopes on all aspects exceeding 30° surrounded by a large body of water serves as an idealised example for showcasing the effects of terrain features on the wind.[9] The hill was covered with 10 meteorological masts (MET-mast) ranging between 20 and 150 m in height, with a LiDAR on the far end of the peninsula and a LiDAR 300 m away on the leeward side of the hill. Based on the 60-day experimental campaign, flow field simulations were validated to understand the exact flow over the terrain feature up to 150 m above ground level (a.g.l.). Although the Bolund experiment provides the benchmark for simulations[10] and data of high-resolution wind profiles[11] for WEA, the peninsula does not accurately represent more complex terrain such as alpine environments.

A more advanced complex terrain study in 2015–2017, specifically aimed at WEA, was carried out in Perdigão, ~150 km northeast of Lisbon, Portugal.[12] Here, two parallel hill ridge lines, separated by approx. 1500 m are covered with wind turbines. Over the three years, various measurement campaigns were held including multiple wind-Doppler LiDARs, which were used in conjunction to resolve three-dimensional wind velocity fields throughout the entire valley.[13,14] Long-term studies of the meso-scale wind profile for WEA have been validated with LiDAR data,[15,16] as well as much smaller-scale turbine wake simulations,[17,18] establishing the use of LiDAR measurements as a valid wind assessment tool over a wide range of spatial resolutions.

The largest instances of complex terrain wind studies, such as the Meso-scale Alpine Project (MAP),[19] have defined the state-of-the-art for the past 20 years. Although the MAP lacks specific wind energy analyses, the project serves as the basis for the validation of numerical weather prediction models in highly complex terrain.[20–23]

Such large-scale wind energy projects provide a wealth of detailed observational data available for high-resolution simulations of their respective study areas, however not all WEA studies merit and require such large investments. WEAs rarely operate more than one LiDAR to perform a wind energy assessment.

Single LiDAR experiments have proven to be capable of forecasting short-term wind fluctuations,[24] as well as suitable for CFD model validation in complex terrain.[25–27] Kristianti *et al.*[28] investigated the complex alpine sites of Les Diablerets and the Lukmanier Pass, both representative of the Swiss Alps, in a comparative study to estimate the wind energy potential at these locations. Here a novel approach pioneered the use of artificial neural networks to combine weather station data with limited wind-Doppler LiDAR measurements to improve WEA. Additionally, the use of a machine learning model, called Wind-Topo,[29] which forecasts 10 m a.g.l. wind speeds at 53 m resolution, was coupled to 100 m a.g.l. wind speeds measured by the LiDAR system using a specific transfer function. Although this transfer function could not yet be validated in a general alpine context, it proves the potential for the combination of different data sources to improve complex terrain WEA without increasing investment costs massively.

State-of-the-art in the industry

The prevalence of terrestrial remote sensing techniques, such as LiDAR experiments, has significantly advanced the ability of WEA in scientific communities. Despite the popularity of LiDAR, conventional MET-masts equipped with anemometers extending up to at least two-thirds of the projected turbine hub height remain the industry standard. This preference is attributed in part to the advantage of obtaining a single-point three-dimensional wind measurement,[30] a feature challenging for LiDAR systems, especially in complex terrains where horizontal wind continuity and uniformity cannot be guaranteed within the scanning cone.[31] Conversely, the assumption that is made to extrapolate MET-mast measurements from two-thirds of the turbine hub height to a complete profile over the swept area by the turbine blades, usually by logarithmic wind profile theory, cannot be applied to extreme complex terrain locations.[32]

While the concept of employing multiple LiDARs appears promising in addressing this challenge, practical issues persist in installation, maintenance, data analysis, cost and instrument availability.[33–35] These complexities demand an advanced understanding of the instruments and the environmental conditions, consequently contributing to elevated operational costs. Moreover, the construction expense, impracticality of installing MET-masts in mountainous regions combined with severe weather and increased risk of natural hazards further underscore the need for alternative approaches.[36]

In response to these challenges, remote sensing methodologies employing a single wind-Doppler LiDAR have gained traction as a cost-effective and efficient alternative. In certain scenarios, sound-wave-based alternatives like Sonic Detection and Ranging (SoDAR) have been explored,[37,38] albeit infrequently. This is primarily due to the limitations in range and concerns about noise pollution associated with SoDARs, positioning single LiDAR WEA methodologies as the most logical step forward for prospective wind parks.[39]

Additionally, an argument can be made for the use of LiDAR profilers instead of free-scanning LiDARs. A LiDAR profiler is designed for measuring vertical atmospheric profiles, emitting laser pulses in fixed directions, often in a conical shape, to capture wind data at a range of altitudes after which it combines the line-of-sight velocities captured in different directions to provide a volume-averaged three-dimensional wind speed of the cone swept by the laser. In contrast, a free-scanning LiDAR can point its laser beam in any direction of a hemisphere following predefined scan patterns, providing more freedom in choosing the line-of-sight wind speeds that are to be measured by the laser beam. This freedom does come at the cost that an experienced user is required to program the suitable scanning patterns and to analyse the data, particularly in complex terrain. The cost of free-scanning LiDARs is nearly three times higher than that of a LiDAR profiler further limiting the incentive for prospective investors to choose this option. Additionally, the free-scanning

LiDARs are heavier, more delicate, and have higher power demands, which drastically limits their range of deployment in complex terrain.

The Gotthard sequential LiDAR transect experiment

It is for these reasons that in this study, we introduce a novel approach employing a *sequential LiDAR* transect experiment utilising a single wind-Doppler LiDAR profiler. The applicability of this methodology is demonstrated in a specific case study focused on a wind farm located on the Gotthard Pass (46.55°N, 8.56°E, 2106 m a.s.l.) connecting the northern and southern alpine regions in Switzerland. Since October 2020, the upper plateau of the pass has been home to five wind turbines, forming the basis of our investigation and providing wind energy data for validation. The Gotthard Wind Park can be considered as the highest degree of complex terrain for wind energy development, characterised by large elevation changes, up- and downwind valleys and steep escarpments within the wind park itself.

This work serves as a proof of concept and as a preliminary showcase of the unique data sets and analyses that are unlocked by the sequential LiDAR experimental methodology, enabling a high-resolution study of the three-dimensional wind field over the entire wind park domain. In addition, we introduce simulated flow fields from the High-resolution Intermediate Complexity Atmospheric Research (HICAR v1.1) model[40] which can resolve terrain-induced flow features at the hectometre scale.

This work intends to demonstrate a novel and resource-efficient method of capturing high-resolution wind field data in complex alpine terrain using a sequential deployment of a single wind-Doppler LiDAR. We supplement this by synoptic weather data, flow field simulations and the continuous wind data from the five wind turbines in the Gotthard wind park. Lastly, we eliminate the spatio-temporal discontinuity of the deployment method by matching different time intervals where the flow over the pass can be considered the same.

In section 2, we provide a detailed description of the Gotthard Pass environment and the wind park site, emphasising the existing and additionally installed study-specific instrumentation used. Section 3 outlines the methodology of the sequential LiDAR transect experiment, and proposes a novel method to analyse sequential LiDAR experiments supplemented by simulations. The results, in section 4, describes the unique wind flow over the sequential LiDAR transect including the site-specific and temporal evolution of wind profiles over complex terrain for the Gotthard wind park, exploring the effects of complex terrain on the airflow in the wind park and how this affects turbine performance. Section 5 discusses key findings and the efficacy of the sequential LiDAR method in view of logistical challenges, providing an outlook into the implications for future WEA studies.

Field site, instrumentation and modelling

The Gotthard wind park is situated atop the Gotthard Pass at an elevation of 2106 m above mean sea level (a.m.s.l.) in the Swiss Alps, at approximately 46.55°N latitude and 8.56°E longitude. Figure 1 shows the Gotthard region with 100 m elevation contour lines, the Gotthard wind park turbines (red diamonds), the topographical points of interest (blue), towns (green triangles) and the surrounding weather stations (orange triangles). This pass is a saddle point between the Northern Urseren valley from the town of Andermatt, canton Uri (approximately 1440 m a.s.l.) and the Southern Bedretto valley at the town of Airolo, canton Ticino (approximately 1210 m a.s.l.). From the Urseren valley, the pass ascends over a distance of 6.8 km along a near-north facing slope with an aspect of 7° up to the summit of the Gotthard Pass. This Upper Reuss valley is characterised by an average slope of 5.6° with minimal deviation and few obstacles to obstruct the wind flow. Subsequently, the pass descends over a distance of 4.3 km along a South-East facing slope with an aspect of 147° called the Tremola valley, featuring an average slope of 12.1°. From the village of Hospental to Airolo, the pass curves gradually towards the East with a radius of curvature of 7.5 km.

The central location of the Gotthard Pass is most frequently a major weather divide for the Northern and Southern Alps. Its north-south orientation provides its distinctive and characteristic feature of exhibiting both North and South Föhn winds, thus often experiencing increased wind flow on the respective lee side of the pass and increased wind energy potential.[28]

Continuing with Figure 1, the contours of the mountain pass are indicated. The southern valley, colloquially known as the Tremola valley, is notably narrower compared to its northern counterpart, with a transverse distance of approximately 300 m at an elevation of 100 m above the valley floor. In contrast, the Northern valley is wider with a valley width of 500–750 m at the 100 m above the valley floor. Moreover, the Tremola valley showcases an orographic prominence, indicated on Figure 2 (orange marker), the Scara Orello mountain (2242 m a.m.s.l.), located 2 km southeast of the upper plateau, blocking the free-flowing streamline of air over the eastern side of the pass in southerly winds. This situation will be discussed in more detail later. To the East and the West of the saddle point, prominent mountains reaching up several

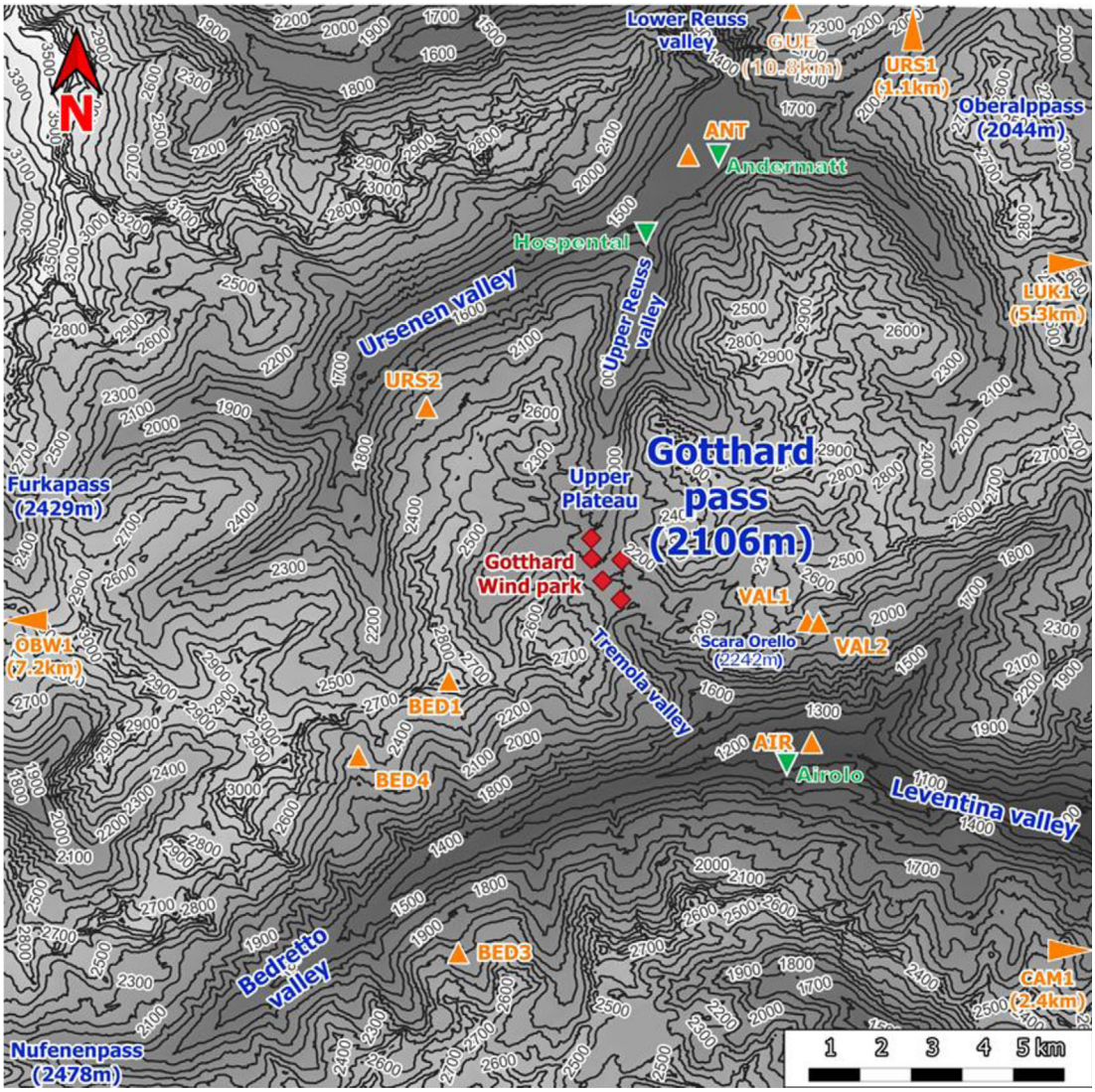

Figure 1. Topographical overview of the Gotthard region.

hundred meters above the upper plateau shelter the wind park from easterly and westerly winds, in fact, they are responsible for the flow channelling customarily observed in the Gotthard wind park.

Zooming in on the Gotthard wind park itself (Figure 3), the Gotthard wind park comprises five turbines positioned on the upper plateau. These turbines are numbered sequentially from North to South, with Turbines 1, 2, 4, and 5 situated on the western side, while Turbine 3 occupies the eastern side. The surrounding landscape features boulders of up to 15 m tall, several small lakes, and grass patches as visible in Figure 2. Notably, the treeline is located far below the upper plateau and thus does not significantly influence the wind flow in the wind park itself. To the Southeast of Turbine 3, a small settlement consisting of low buildings and shelters is observed, exhibiting a similar surface roughness to the boulders present elsewhere on the upper plateau by estimate.

Instrumentation overview

The five wind turbines in the Gotthard wind park are Enercon E92 turbines with a rotor diameter of 92 m mounted upon a 98 m mast. They are specified for 2.35MW rated power, and a cut-in, rated, and cut-out wind speed of 2 ms^{-1}, 11 ms^{-1} and 25 ms^{-1}, respectively. Table 1 provides details regarding the geographical coordinates, elevation, and characteristics of these turbines, as well as all instrumentation employed in this study. Firstly, the sequential LiDAR data set includes wind profiles at twenty range gates focused around the turbine height of the wind park, starting with range gates at 40 m up to 160 m increasing by steps of 10 m. After which, the range gates increase by steps of 20 m up to 300 m, providing a

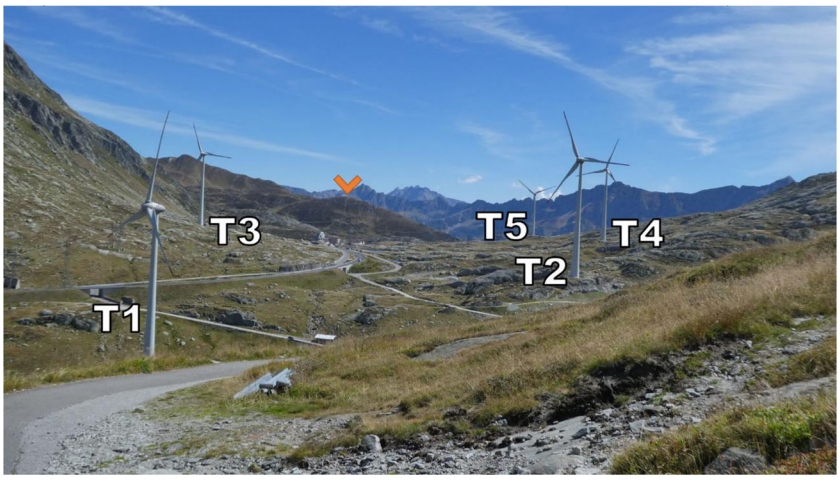

Figure 2. The Gotthard Pass in summer seen from the north-western side of the Upper Plateau.

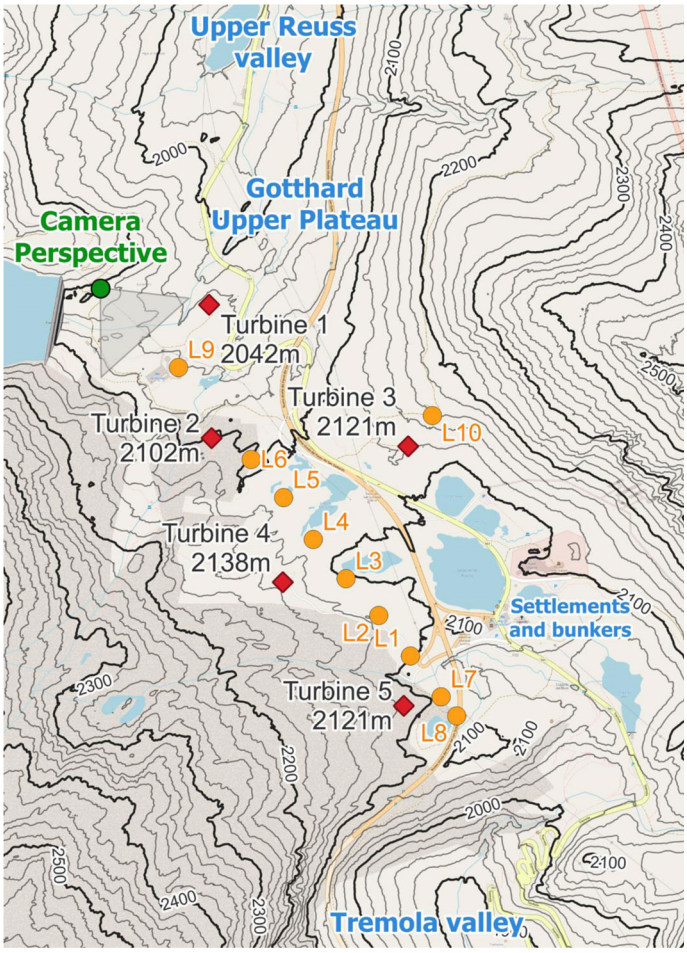

Figure 3. The Gotthard Upper Plateau, featuring wind turbines (red diamonds), LiDAR locations (orange dots), and the camera perspective of Figure 2.

comprehensive profile of the wind park by including wind speeds well above the turbines. A range gate is a specific range interval from the LiDAR instrument within which it measures the wind speed and direction by analysing the Doppler shift of the returned signal within this interval.

Table 1. Instrumentation and data availability. Easting and Northing coordinates in the Swiss Coordinate system LV95 (EPSG:2056).

Dataset	Station	Data access	Easting [m]	Northing [m]	Altitude [m]	Period [ISO 8601, UTC]	Description
LiDAR transect	L1	Available via Envidat	2686269	1156520	2101	2023-06-19T14:20Z - 2023-06-21T20:50Z	Origin of transect
	L2		2686173	1156369	2116	2023-07-14T11:10Z - 2023-07-14T11:00Z	+150m along transect
	L3		2686074	1156747	2103	2023-07-14T11:20Z - 2023-07-21T08:50Z	+300m along transect
	L4		2685975	1156862	2110	2023-07-21T13:00Z - 2023-07-27T09:40Z	+450m along transect
	L5		2685885	1156869	2112	2023-07-27T15:50Z - 2023-08-08T11:00Z	+600m along transect
	L6		2685787	1157097	2097	2023-08-11T12:10Z - 2023-08-12T09:10Z	+750m along transect
	L7		2686362	1157400	2096	2023-08-18T14:20Z - 2023-08-29T09:10Z	-150m along transect
	L8		2686409	1156444	2089	2023-08-29T10:40Z - 2023-09-04T07:00Z	-225m along transect
	L9		2685567	1157235	2063	2023-09-04T15:50Z - 2023-09-12T06:30Z	+1100m along transect
	L10		2686324	1157325	2157	2023-09-12T11:00Z - 2023-09-20T00:00Z	Off transect near Turbine 3
Wind Turbines (AET)	T1	N/A	2685655	1157555	2140	2020-10-29T09:50Z - 2023-09-20T00:00Z	
	T2		2685668	1157159	2200	2020-10-08T16:00Z - 2023-09-20T00:00Z	
	T3		2686253	1157143	2219	2020-10-19T17:30Z - 2023-09-20T00:00Z	On west-facing slope
	T4		2685886	1156734	2236	2020-11-23T11:30Z - 2023-09-20T00:00Z	
	T5		2686251	1156372	2219	2020-11-16T17:40Z - 2023-09-20T00:00Z	

Table 1. *Continued*

Dataset	Station	Data access	Easting [m]	Northing [m]	Altitude [m]	Period [ISO 8601, UTC]	Description
Weather stations (SLF)	BED1	Publicly available by request to WSL SLF IMIS	2682908	1154748	2963	2023-06-19T00:00Z - 2023-09-20T00:00Z	Mountain top (West)
	BED3		2683169	1149445	2101	2023-06-19T00:00Z - 2023-09-20T00:00Z	Bedretto valley (North facing)
	BED4		2681160	1153250	2305	2023-06-19T00:00Z - 2023-09-20T00:00Z	Bedretto valley (South facing)
	CAM1		2696885	1148709	2668	2023-06-19T00:00Z - 2023-09-20T00:00Z	Leventina valley (North facing)
	GOS3		2689425	1167908	2209	2023-06-19T00:00Z - 2023-09-20T00:00Z	Mountain ridge (North)
	LUK1		2703254	1163181	3040	2023-06-19T00:00Z - 2023-09-20T00:00Z	Mountain top (East, far)
	OBW1		2666706	1155765	2733	2023-06-19T00:00Z - 2023-09-20T00:00Z	Mountain top (West, far)
	URS1		2691804	1169246	2784	2023-06-19T00:00Z - 2023-09-20T00:00Z	Mountain top (North)
	URS2		2682405	1160066	2169	2023-06-19T00:00Z - 2023-09-20T00:00Z	Urseren valley (North facing)
	VAL1		2689900	1156001	2450	2023-06-19T00:00Z - 2023-09-20T00:00Z	Tremola valley (Eastern mountain top)
	VAL2		2690126	1155980	2628	2023-06-19T00:00Z - 2023-09-20T00:00Z	Tremola valley (South facing)
Weather stations (MeteoSwiss)	ANT	Pubicly available by request to MeteoSwiss	2687445	1165044	1435	2023-06-19T00:00Z - 2023-09-20T00:00Z	North exit of Gotthard pass (Andermatt)
	AIR		2690019	1153645	1157	2023-06-19T00:00Z - 2023-09-20T00:00Z	South exit of Gotthard pass (Airolo)
	GUE		2690087	1167480	2286	2023-06-19T00:00Z - 2023-09-20T00:00Z	Mountain ridge Gütsch (North, 11km)
HICAR v1.1		Data available upon request	Availabe throughout the Gotthard domain 50m horizontal resolution following the LV95 (EPSG:2056) coordinate system.			2023-06-01T00:00Z - 2023-09-22T00:00Z	50m spatial resolution, 32 levels from at [10, 33, 61, 95, 135, 1885, 246, 328m a.g.l., etc.]

This large array of wind profiles is complemented by both wind speed and power metrics from individual turbines, which are made available by the turbine operators, Azienda Elettrica Ticinese. Data from eleven mountain weather stations operated by the Swiss Institute for Snow and Avalanche Research.[41] Additionally, three weather stations in the vicinity of the Gotthard Pass and one at a nearby wind park of similar elevation are used, all of which are operated by the Swiss Federal Office for Meteorology and Climatology.[42] Finally, the HICAR v1.1 model is employed at a resolution of 50 m for the duration of the campaign and throughout the entire Gotthard domain as indicated in Figure 1.

LiDAR details

The VAISALA WindCube v2.1 WLS7-1726 profiler was the sole remote-sensing wind measurement instrument used for this campaign, sequentially situated between the five turbines in the Gotthard wind park. The LiDAR profiler makes use of five pulsed laser beams, which are magnetically controlled by the instrument with 0.8 s of exposure in a vertical stare position after the instrument moves the laser in 0.2 s to its next positions: North, East, South, and West with 28° angle from the vertical axis with the same exposure time. The return signal of the 1543 nm, 30 mW mean power laser is recaptured, and based on the Doppler shift of the five line-of-sight laser beams a three-dimensional wind vector is determined for each range gate in the profile.

This specific instrument logs data at two temporal resolutions: one-second, individual beam data, as well as 10-min averaged data, which can be used for both relatively high-level wind profile and shear structure analysis as well as turbulence intensity calculations for WEA purposes. Both time resolution data sets are made available via the instructions in Table 1.

Sequential LiDAR transect

To analyse the evolution of wind patterns across the complex terrain of the Gotthard wind park, a sequential LiDAR transect was executed. This transect, conducted over three months from 19 June to 20 September 2023, focuses on the upper plateau where the mountains slopes channel the prevailing wind in the downwind direction. It is noted that, despite the overall complex terrain of the Gotthard Pass, the turbines and LiDAR transect are aligned along a topographically channeled plateau. As a consequence, the flow conditions encountered here are less complex than at exposed hilltop or ridge locations, where flow inclination and flow separation may violate the horizontal homogeneity assumption required for ground-based Doppler LiDAR wind retrievals. This represents a limitation of the present study.

The transect includes nine distinct LiDAR locations, positioned at regular increments, plus one additional deployment near Turbine 3 on the eastern side of the plateau. This LiDAR transect aims to provide an extensive collection of wind profiles along the prevailing wind direction axis of the wind park, emphasising high-resolution, three-dimensional wind velocity fields unattainable through conventional single LiDAR deployments.

The LiDAR transect logistics involved the transport of the LiDAR by vehicle over the various wind turbine servicing roads. When the closest point to the sequential LiDAR position was reached, the LiDAR was carried up to 200 m away from infrastructure over rough terrain by two individuals. It was placed on a levelled wooden palette to minimize movement in soft soil and to protect against flooding. Power was accessed through extension cables up to 330 m long, connected to the grid via different wind turbines. The two extremes of the transect were defined by distances of −225 m and +1’100 m from the origin defined at L1, with the former constrained by a highway crossing and the latter avoiding potential wake interference from Turbines 1 and 2.

A radiation-shielded combined pressure, temperature, and humidity sensor was placed near the LiDAR 1 m above the ground which is solely used to calculate the local air density. This sensor provides 10-minute averaged atmospheric variables at the LiDAR site. The LiDAR wind profiles could be monitored remotely via a 4G connection using the LTE network available on the Gotthard Pass, and the data was extracted on a near-weekly basis when the LiDAR was moved to its new position.

In some cases, data gaps are observed within the LiDAR transect which occurred due to disconnection or power loss from the grid from which the LiDAR was powered. In particular, heavy thunderstorms and hail storms which are common in the Swiss high-alpine region were prone to shutting down the LiDAR measurements. Due to long access time to the study area, the LiDAR sometimes could not be serviced promptly after shutdown further extending the data gaps.

The nine sequential LiDAR locations, spaced at 150 m increments, mostly covered the western part of the wind park. The orientation of the transect was based on the prevailing wind direction extracted from the Swiss Wind Atlas providing wind rose information at 100 m above the ground level, at 100 m horizontal and 25 m vertical resolution.[43] Additionally, a tenth LiDAR location near Turbine 3 on the eastern side aimed to capture representative wind profiles from the eastern sector.

Diagnostic wind model HICAR v1.1

To provide a simulated 3D wind field for the spatial and temporal extent of the study, the High-resolution Intermediate Complexity Atmospheric Research (HICAR) model was used.[40] HICAR was chosen over an LES model due to its fast runtime, which is orders of magnitude faster than a conventional atmospheric model. This enables simulation of the entire observational period, instead of only a few events. Key to HICAR's computational efficiency is its use of a diagnostic, incompressible mass-conserving wind solver in place of the full Navier-Stokes equations. The wind solver, first introduced by,[44] has seen widespread use and development in the pollutant transport community in the decades since. When solving for the flow field, effects of terrain blocking or channelling are considered depending on the ambient atmospheric stability and obstacle height. In addition to the diagnostic solver, HICAR uses a parameterization for leeside recirculation and slow down. The resultant flow fields have been validated in complex terrain using a wind LiDAR, where[45] found that HICAR can resolve flow features induced by terrain, but notably not buoyancy-driven turbulent features.

The HICAR simulations utilized two nests, one at a 1km resolution extending roughly 100km beyond the boundaries of the study domain, and a second at a 50m resolution covering the study domain. The outer domain was forced hourly with reanalysis data from the COSMO1 model,[46] which provided operational forecasts over Switzerland until 2024. HICAR was run with the Morrison microphysics scheme, the RRTMG radiation scheme with terrain shading, NoahMP land surface model, and a 3rd order accurate advection scheme. The physics parameterizations affect both the density of the atmosphere and the atmospheric stability, ultimately influencing the diagnostic wind solver.

Methodology

The primary challenge in analysing sequential LiDAR measurements lies in addressing the inherent lack of spatio-temporal continuity within the data set. As the weather is dynamic throughout the three-month measurement campaign, a method of inter-comparison between the different LiDAR deployments along the transect is developed that evaluates the similarity of atmospheric conditions across time. We expect that similar synoptic wind conditions across the pass when similar wind vectors are measured at all five nacelles in the Gotthard wind park. Firstly, nacelle anemometer data from the turbines is assessed based on vectorial wind speed differences, after which eight characteristic features of the atmosphere and flow features based on the HICAR simulations are considered.

Nacelle wind data

Firstly, wind velocity is measured on the nacelles of the five turbines situated on the upper plateau. By considering the wind vectors measured at the nacelles of each turbine, similar inflow characteristics can be deduced from which these common time frames can be compared over the entire sequential LiDAR study to show the evolution of wind profiles along the upper plateau.

Nacelle wind velocities are collected by anemometers located at 98 m above ground level. These stations measure average wind speed and direction at 10-minute intervals, but do not include a measure for turbulence intensity. Within the time domain of the sequential LiDAR campaign, the horizontal wind speed components U and V are calculated for the total of 13'295 10-minute intervals covering the entire campaign period.

As shown in Figure 4, the vectorial difference in wind speed for each turbine is evaluated for each pair of 10-minute intervals (i.e., $5 \cdot 13'295^2/2 \approx 4.4 \cdot 10^8$ pairs are evaluated) in the data set (Equation 1).

$$\begin{bmatrix} \Delta V_{ij}^{T_1} \\ \Delta V_{ij}^{T_2} \\ \Delta V_{ij}^{T_3} \\ \Delta V_{ij}^{T_4} \\ \Delta V_{ij}^{T_5} \end{bmatrix} = \begin{bmatrix} |\vec{v}_i^{T_1} - \vec{v}_j^{T_1}| \\ |\vec{v}_i^{T_2} - \vec{v}_j^{T_2}| \\ |\vec{v}_i^{T_3} - \vec{v}_j^{T_3}| \\ |\vec{v}_i^{T_4} - \vec{v}_j^{T_4}| \\ |\vec{v}_i^{T_5} - \vec{v}_j^{T_5}| \end{bmatrix} \tag{1}$$

$$match(\vec{v}_i^{L_{x_1}}, \vec{v}_j^{L_{x_2}}) = \max_{T_x \in \{T_1,T_2,T_3,T_4,T_5\}} \Delta V_{ij}^{T_x} \leq V_{margin} = 0.5\, m/s \tag{2}$$

Where $\vec{v}_i^{T_x}$ and $\vec{v}_j^{T_x}$ $[ms^{-1}]$ are turbine nacelle wind velocities at time interval i and j, respectively, for turbine $T_{x \in \{1,2,3,4,5\}}$. $\Delta V_{ij}^{T_x} [ms^{-1}]$ is the vectorial difference in the wind speed. If all five turbines exhibit a wind velocity within the given error margin V_{margin} = 0.5 ms^{-1} (Equation 2), the pair is considered to be a match. This error margin is chosen to be approximately 10% of the mean wind speed of the wind park, whilst remaining higher than the error specification of the anemometer.

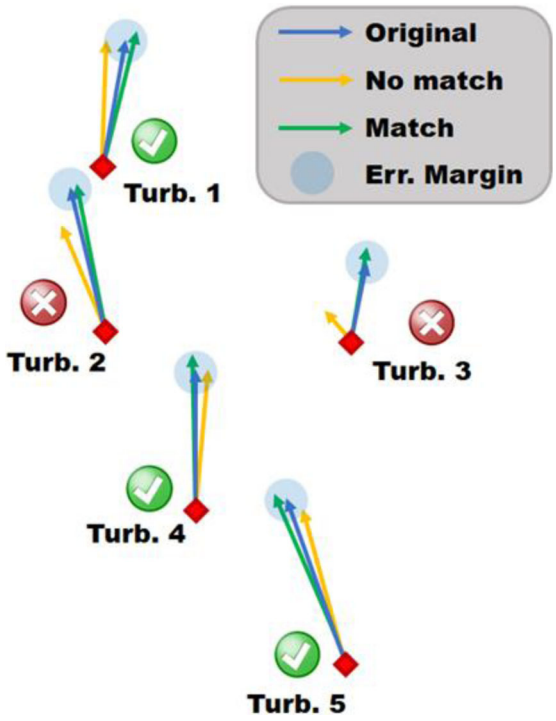

Figure 4. Schematic of the matching algorithm, visualize three different snapshots by coloured vectors.

An example, shown in Figure 4, shows that for Turbines 1 and 5, the green and yellow vectors are within the blue error margin but not within the margin of each other. Resulting in the green vectors forming a match with blue, whilst the yellow vectors do not.

Since the matching algorithm described above only requires the wind turbine wind velocity data points, there are several cases where the timestamp does not have a corresponding LiDAR wind profile due to LiDAR data gaps. Approximately 4'000 out of 6'000 matches have LiDAR data available for at least two wind profiles ($\vec{v}_i^{L_{x_1}}$ & $\vec{v}_j^{L_{x_2}}$) from the matched timestamps to make inter-comparison possible (Equation 3).

$$\exists \vec{v}_i^{L_{x_1}}, \vec{v}_j^{L_{x_2}} | L_{x_1}, L_{x_2} \in \{L_1, L_2, \ldots, L_{10}\}, L_{x_1} \neq L_{x_2}, match(\vec{v}_i^{L_{x_1}}, \vec{v}_j^{L_{x_2}}) \tag{3}$$

Where L_{x_1} and L_{x_2} indicate two unique LiDAR locations, for both of which the LiDAR profiler has measured a wind velocity at the matched time interval *i.* It should be noted that Equation 3 describes only the minimum requirement for a match to be formed, in many cases more than two different LiDAR positions are in the same match, and multiple time intervals can exist for the same LiDAR position (Equation 4). However, such a match for *i* does not necessarily imply that *j* and *k* are also a match with each other, as their wind vectors could potentially be on the other side of the error margin (consider Turbine 1 in Figure 4).

$$match(\vec{v}_i^{L_{x_1}}, \vec{v}_j^{L_{x_2}}, \vec{v}_k^{L_{x_3}}) \rightarrow match(\vec{v}_i^{L_{x_1}}, \vec{v}_j^{L_{x_2}}), match(\vec{v}_i^{L_{x_1}}, \vec{v}_k^{L_{x_3}}) \tag{4}$$

HICAR characteristic features

Building on the nacelle-based matching, we refine the inter-comparison by introducing eight characteristic parameters derived from the HICAR v1.1 mesoscale model. The model provides wind fields on a 50 m horizontal grid with 32 vertical levels, which were interpolated to the nacelle positions (98 m a.g.l.), and to the ten LiDAR locations with their respective range gates.

From these interpolated fields, along with local measurements, we define eight parameters that characterise the inflow conditions from the Gotthard wind park domain, which is chosen to be around Turbine 4 as it is the most central turbine:

(1) Global horizontal irradiation (GHI [Wm^{-2}]), a direct output of HICAR from the grid cell of Turbine 4.

(2) Atmospheric stability ($\frac{\partial\theta}{\partial z}[Km^{-1}]$), calculated from the potential temperature gradient from 10 m to 247 m a.g.l. (7 levels) at the Turbine 4 grid cell.

(3) Vertical shear magnitude ($|\frac{\partial\vec{v}}{\partial z}|[ms^{-1}]$), derived from the horizontal wind vectors from 10 m to 247 m a.g.l., spatially averaged over the transect spanning 2 km.

(4) Variance of the vertical turbulence (W'^2 [$m^2 s^{-2}$]), derived the variance of the vertical wind from 10 m to 247 m a.g.l., spatially averaged over the transect spanning 2 km.

(5–6) Synoptic wind components (U_{synop} & V_{synop} [ms^{-1}]) derived from the 5 km level of HICAR (level 20) from the grid cell of Turbine 4.

(7–8) Transect-averaged wind components ($U_{transect}$ & $V_{transect}$ [ms^{-1}]) derived from level 3–5 (61–136m a.g.l.) of HICAR.

Each parameter is subsequently standardised by z-scaling to zero mean and unit variance. We are unable to compare the HICAR wind vectors at the wind turbine nacelles with the in-situ data measured by the anemometers due to the flow distortion of the nacelle which is not simulated.

Analogous to the method applied for matching turbine nacelle wind data, we proceed with filtering the matches further using these eight characteristic features by examining their coherence across multiple wind profiles. As this filtering will reduce in size the majority of nacelle data, we only consider combinations of at least 5 different LiDAR wind profiles from distinct locations (90 matches in total).

For each combination, we calculate the standard deviation across all eight characteristic features simultaneously. As a baseline, random selections of 5 to 27 profiles yield standard deviations that are consistently high, with standard deviation values typically between 0.926 ± 0.053 and 0.983 ± 0.015 for 5 to 27 randomly selected wind profiles, respectively.

To identify profiles that are meaningfully related, we define a threshold standard deviation of 0.6 across all eight features. Combinations where the standard deviation for all features falls below this threshold are considered a match, indicating strong coherence between the selected profiles. This approach is analogous to the wind turbine analysis, where a deviation below 0.5 m s^{-1} in nacelle wind measurements is used to define a valid match.

This standard deviation threshold of $\sigma < 0.6$ is chosen based on the combined likelihood of a random selection fulfilling these criteria, with the exception of atmospheric stability for which all timestamps should exhibit the same class (stable, neutral, unstable). All matching criteria are summarised in Table 2. By testing over a large number of combinations (10^7 random selections for 5 and 27 wind profiles) we estimate that the probability of a random selection satisfying this strict requirement corresponds to between 3.0 σ (< 0.28%) and 5.3 σ (<10^{-7}) for the matches made with the nacelle wind data.

Table 2. Threshold criteria that are required for the matching algorithm.

Feature	Threshold
Turbine nacelle wind speed (98m a.g.l.)	$\Delta V_{ij}^{T_x} \leq 0.5\ ms^{-1}$
Global horizontal Irradiation	$\sigma GHI \leq 186\ Wm^{-2}$
Atmospheric stability (10-247m a.g.l.)	Same class: Stable ($\frac{\partial\theta}{\partial z} > 0.002\ Km^{-1}$), Unstable ($\frac{\partial\theta}{\partial z} \leq -0.002\ Km^{-1}$), and Neutral ($-0.002 < \frac{\partial\theta}{\partial z} \leq 0.002\ Km^{-1}$).
Vertical shear magnitude (10-247m a.g.l.)	$\sigma\sigma|\frac{\partial\vec{v}}{\partial z}| \leq 0.005\ s^{-1}$
Variance of the vertical turbulence (10-247m a.g.l.)	$\sigma w'^2 \leq 0.15\ m^2 s^{-2}$
Synoptic wind (5km a.m.s.l.)	$\sigma U_{synop} \leq 5.16\ ms^{-1}$ $\sigma V_{synop} \leq 4.55\ ms^{-1}$
Transect-averaged wind (10-247m a.g.l.)	$\sigma U_{transect} \leq 1.45\ ms^{-1}$ $\sigma V_{transect} \leq 0.52\ ms^{-1}$

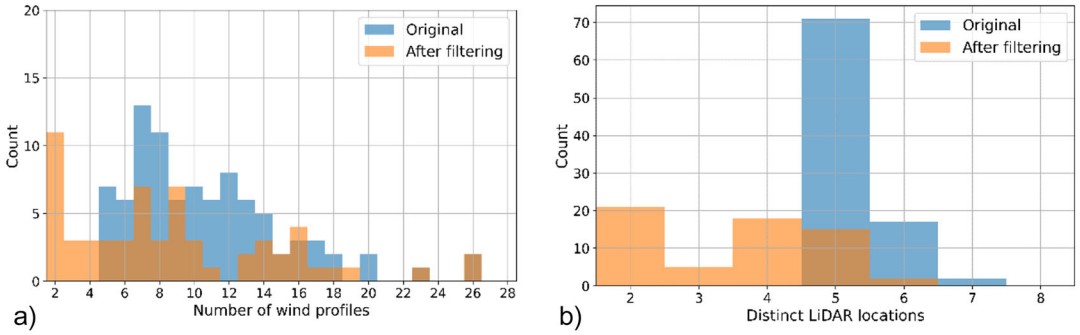

Figure 5. a) Match size and b) LiDAR locations before and after HICAR characteristic feature filtering.

Which is statistically unlikely to occur randomly, thus concluding that different previously matched wind profiles passing these strict criteria, are indeed sufficiently related in both wind pattern as well as atmospheric conditions.

To avoid the brute-force exhaustive computation, we implement a greedy "drop-until-threshold" algorithm. For each existing match of at least 5 wind profiles, we iteratively remove profiles that contribute most to exceeding the standard deviation threshold. Starting with the worst offending profile, we drop one at a time, recalculating the combined standard deviation after each removal, until the match satisfies the criteria or there are no wind profiles left to drop. While the algorithm ensures that the overall standard deviation is reduced below the threshold, individual values may still fall outside the specified limits.

Applying the stricter matching criteria to the nacelle-based matches reduces not only the total number of matches identified but also the composition of each match. For example, a nacelle-based match of 20 different wind profiles over 6 distinct LiDAR locations, that is filtered by the stricter HICAR criteria, could be reduced to only 10 profiles over 3 LiDAR locations. This filtering step is summarised in Figure 5, which shows the number of wind profiles, and distinct LiDAR locations for these matches before and after filtering. However, the resulting match can be considered significantly more robust as it not only has similar wind vectors at the five turbines, but also similar global radiation, atmospheric stability, shear, vertical turbulence, transect wind vectors and synoptic winds.

In total 35 unique matches with at least 4 different LiDAR locations are identified. These matches exhibit consistent wind and atmospheric conditions along the Gotthard Wind Park with LiDAR wind profile measurements along the pass. The 35 matches differ from another in general wind patterns and atmospheric conditions, which allows for a comprehensive analysis of the typical wind patterns that are observed on the Gotthard pass, which can help in explaining the turbine efficiency. The matching algorithm methodology is summarised in a flowchart shown in Figure 6.

Results

Having established a robust matching algorithm for the sequential LiDAR measurements along the transect in the Gotthard wind park, the matched wind profiles can now be visualised along the transect, with all three wind components along the pass at any height of the measurement range. Previously, such visualisations were only possible using a triple wind-Doppler LiDAR setup with synchronised measurements.

LiDAR horizontal flow homogeneity assumption

In complex terrain, concerns may arise regarding the applicability of Doppler wind LiDARs, as horizontal flow inhomogeneities can violate the homogeneity assumption underlying the retrieval of vertical wind profiles. The WindCube V2.1 profiler employs four beams inclined 28° from the vertical, corresponding to a horizontal separation of approximately 100 m between opposing beams at 100 m height. To evaluate potential impacts of horizontal inhomogeneity, we analysed flow field simulations across representative distances of 100 m (at 100 m height) and 300 m (at 300 m height) in all four cardinal directions. This shows that the mean biases in all wind components remain below 0.1 ms^{-1}, which is negligible relative to the intrinsic measurement uncertainty of the LiDAR. Standard deviations are generally below 0.5 ms^{-1}, with slightly larger values in the north–south direction, attributable to valley channelling, and in the east–west direction near the surface, likely related to surface effects. Although the flow field simulations do not represent thermally driven flows such as katabatic or anabatic winds, which may increase variability in reality, the observed deviations are on the order of the intrinsic error of the LiDAR, thus supporting the validity of the horizontal homogeneity assumption. Consequently, LiDAR-derived vertical profiles can be interpreted without additional corrections. Additionally, at the horizontal scales relevant for the LiDAR measurements, the HiCAR v1.1 model resolution (50 m) does not

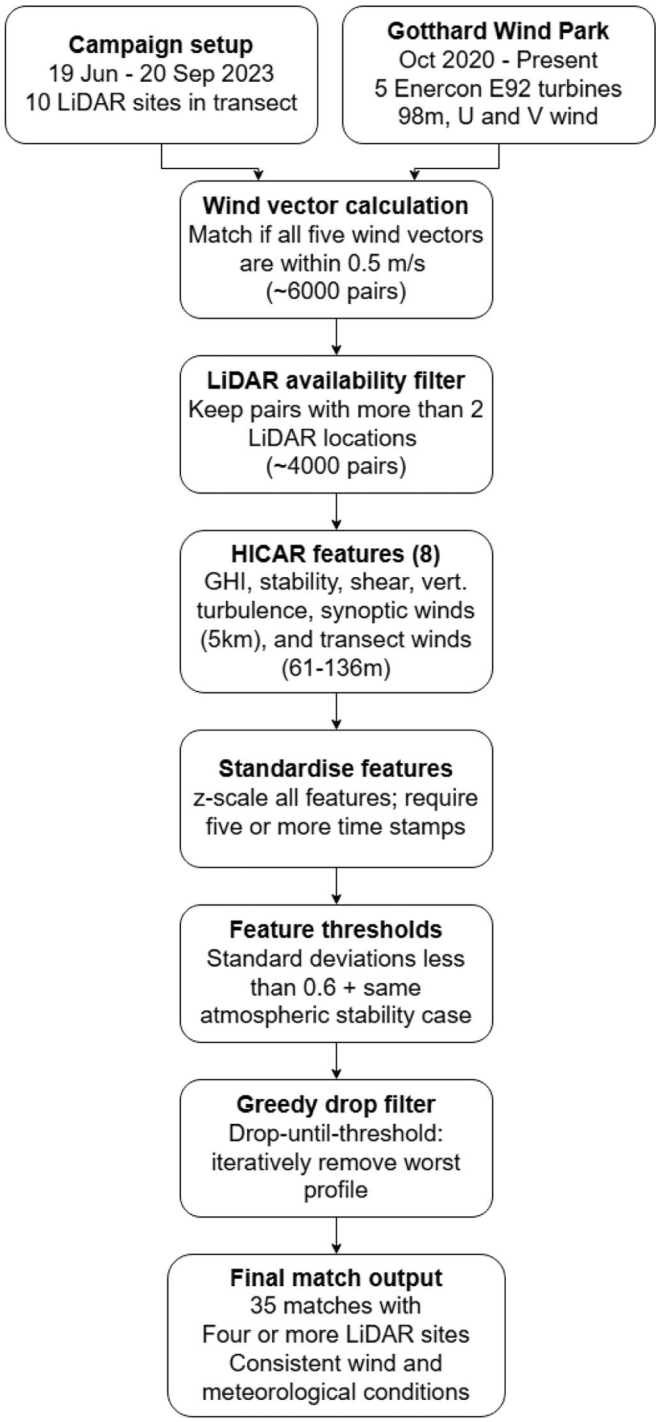

Figure 6. Flowchart of the matching algorithm methodology.

resolve sub-grid flow variability within the LiDAR sampling volume. Consequently, model-derived mean flow fields appear horizontally smooth over the transect length and are therefore not well suited to visually illustrate the LiDAR horizontal homogeneity assumption.

Gotthard pass wind characteristics

Firstly, the wind patterns observed on the pass at the height of the turbine nacelles are illustrated by wind roses in Figure 7. Here, northerly winds can be observed to be generally stronger than southerly winds. Particularly, wind speeds above the

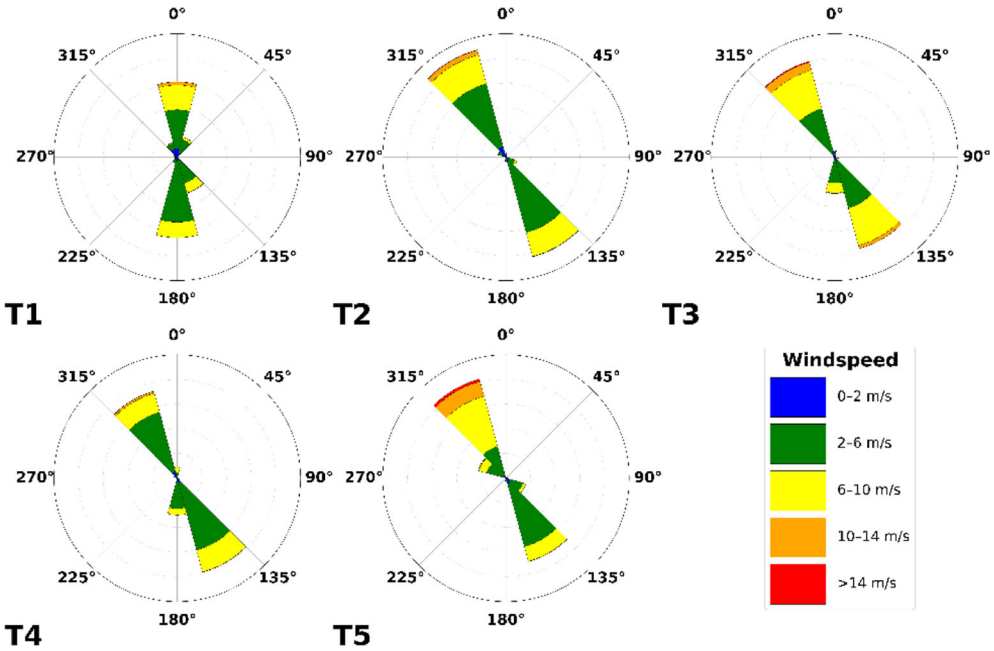

Figure 7. Wind roses of the five turbines in the Gotthard Wind Park based on all three years of data since its construction.

rated wind speed of the E92 turbine are much more prevalent. We define southerly winds as originating between the azimuths 75° and 255° and northerly wind from the remaining 180° sector. These distinct differences can be recognised in the Weibull distributions (Equation 5), which are split based on the two prevailing wind directions in Figure 7.

$$f(v) = \frac{k}{\lambda}\left(\frac{v}{\lambda}\right)^{k-1} \exp - (v/\lambda)^k \tag{5}$$

Weibull parameters scale shape k [-] and λ [m/s] parameters, and the measured mean wind speed $|\vec{v}|$ [m/s], split for northerly and southerly winds ($75° < \theta \leq 255°$) for the Gotthard wind turbines.

In Figure 8, the wind roses at approximately 100 m above the ground of all the turbine and LiDAR locations are shown. The blue wind roses that are generated from LiDAR data do not exhibit the correct proportions in the frequency of the wind direction, as often only one week of data is available at a given location. However, the wind roses illustrate the spatial progression of the general wind direction along the Gotthard wind park well. Particularly, the differences for northerly and southerly winds at any given location on the pass can be observed.

Matching algorithm statistics

Figure 9 shows the distribution of LiDAR locations throughout the Gotthard Transect Experiment in orange. In the majority of the campaign period, there were no LiDAR wind profiles available (N/A column). The distribution across the 10 LiDAR sites varies considerably due to the weekly relocation of the instrument, which often included periods of missing data as the experiment was not tended to on a daily basis. As a result, some sites are more present in the final matched dataset than others. In particular, L2, L5 and L9 dominate the distribution because these sites happened to sample a large number of northerly winds. As discussed in more detail in the following subsection, the northerly winds are more likely to be matched as this wind regime seems to be more consistent in wind speed as well as the steadiness of the streamlines, exhibiting less shear and veer than the Southerly winds.

Figure 10 presents the distribution of matched timestamps as a function of the hour of day. The matches are not uniformly spread, like the original transect experiment dataset. Distinct diurnal peaks are observed where a majority of matches occurring during daytime hours, when solar heating promotes boundary-layer turbulence and characteristic vertical wind shear patterns which are repeating often. A second cluster can be observed during night hours (23-01 UTC), likely reflecting stable nocturnal conditions that are also well represented in the HICAR characteristic parameters. Finally, peaks occur near the end of the night (06 UTC) and near the end of the afternoon (18 UTC), capturing transient stability transitions. Although the hour of day itself was not an explicit matching variable, these results demonstrate that the

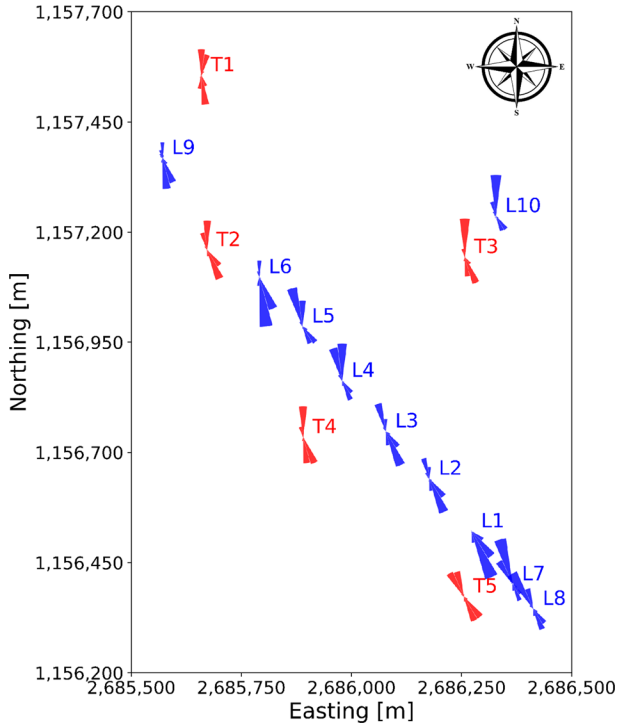

Figure 8. Spatial progression of wind direction over the Gotthard wind park, illustrated by wind roses at around 100 m above ground level.

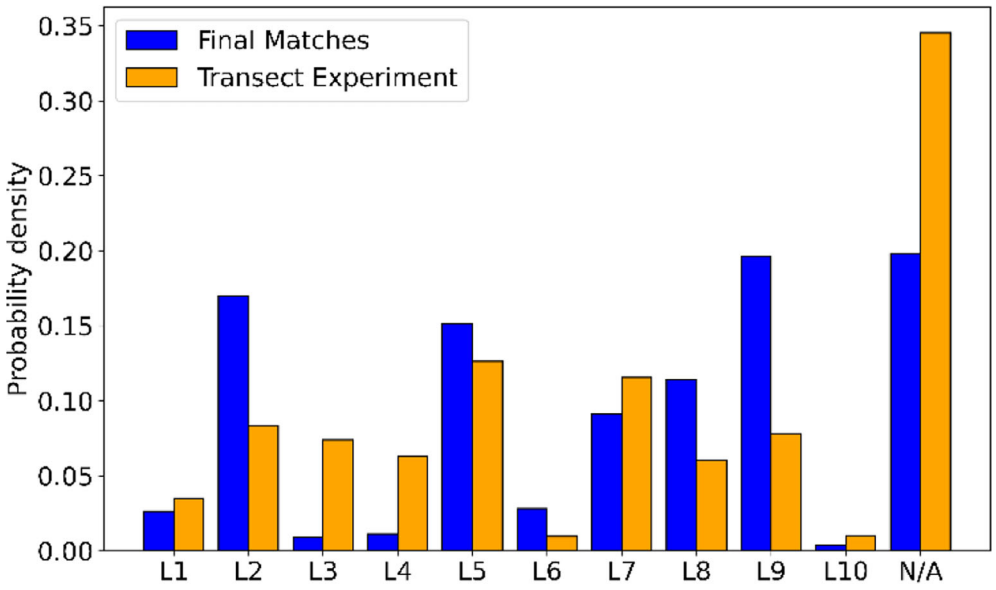

Figure 9. Frequency of LiDAR locations, matches vs. full dataset.

matching algorithm does also distinguish different parts of the diurnal cycle, based on the forcing data in the HICAR simulations alone.

Transect wind profile evolution

To illustrate the variability of flow conditions across the transect, we highlight three representative matched wind profiles (A–C). Of the 35 matches with at least four lidar profiles, 26 (74%) correspond to northerly winds, 5 (14%) to southerly

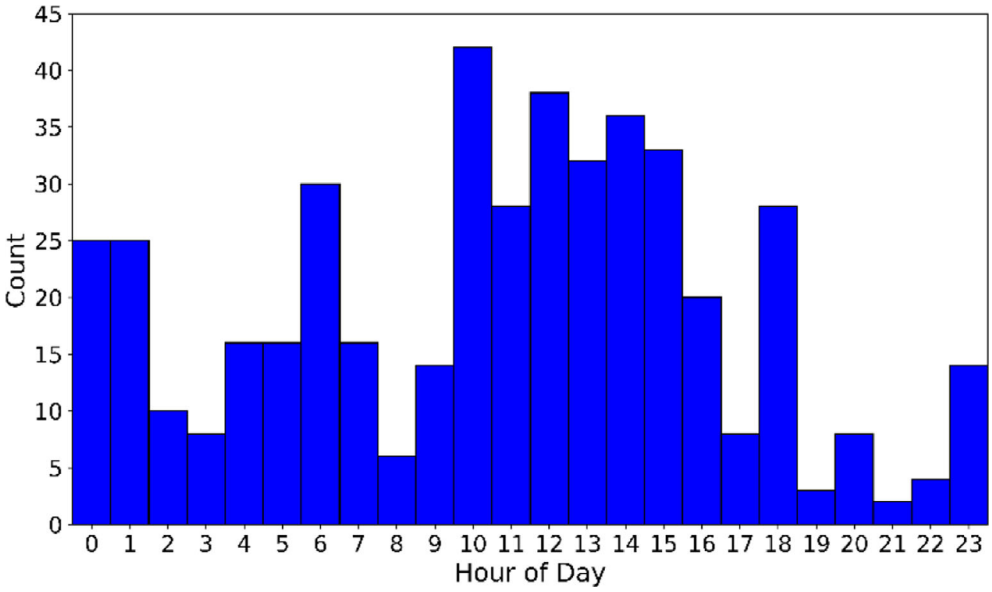

Figure 10. Distribution of time in final matches.

winds, and 4 (12%) to low-wind cases where no dominant wind direction could be determined. Figure 11 and Figure 12 present these three selected matches in side and top view, respectively, while Table 4 summarises the associated timestamps and characteristic parameters from the matching algorithm.

Match A (northerly winds): This case represents the dominant flow regime during the experiment: daytime northerly winds under unstable conditions, with relatively strong incoming solar radiation ($GHI \approx 624\ Wm^{-2}$). The wind speed is relatively strong and shows little vertical shear due the strong vertical mixing as reflected by the HICAR simulations. At L9, the wake of Turbine 1 can be identified in the lower part of the profile, while further downstream the flow is slightly deflected upward before curving downward again near L7–L8. Only minor veering (a few degrees) is visible throughout the profile, which can be considered negligible. And near L8 a shearing effect can be consistently observed in the lower 100m of the wind profile, which can be attributed to the small north facing escarpment on which T5 is located. Overall, this northerly pattern is representative of the majority of final matches. The most consistent effect is a modest channelling that accelerates the flow towards the southern turbines (T3 and T5), which in turn produces relatively more power compared to the northern turbines (T1, T2, T4). Because the structure of northerly flows is fairly uniform across the matches, we only show one representative example here.

Matches B and C (southerly winds). In contrast, the two southerly cases were both matched under weak solar input ($GHI \approx 50\ Wm^{-2}$), occurring around 06 UTC or during nocturnal hours. Given summer daylight savings in Switzerland (UTC+2), these periods still correspond to pre-sunrise conditions. Both cases are characterised by stable atmospheric stratification, which enhances vertical. In Match B, a particularly interesting feature appears: a reversal in flow direction around L2, with signs of shear already emerging upstream at L7–L8. The cause of this localized reversal is not entirely clear but may be linked to terrain-induced flow separation or local recirculation in stable conditions. This flow reversal is observed regularly in other wind profiles with slow southerlies. The wind also decelerates near the end of the transect. Match C shows a similar downstream deceleration but without reversal; instead, strong localised shear is evident near Turbine 5 (and, in other cases, also at Turbine 3), which likely impacts turbine efficiency. These two cases highlight the more complex flow behaviour under southerly winds, where we examine these shear effects and their implications for turbine performance in more detail.

Wind shear and veer

For northerly winds, shear is consistently observed near L8 at the southern end of the transect, largely caused by the small hill where Turbine 5 is located. Under southerly winds, however, the more dominant influence is the Scara Orello mountain (2242 m) in the Tremola Valley (Figure 12). This prominence rises about 140 m above the wind park and creates a clear separation between air layers. Higher-altitude winds pass over the obstacle and continue northwest along the Tremola Valley, while the lower flow is diverted around the mountain and redirected northward over the pass.

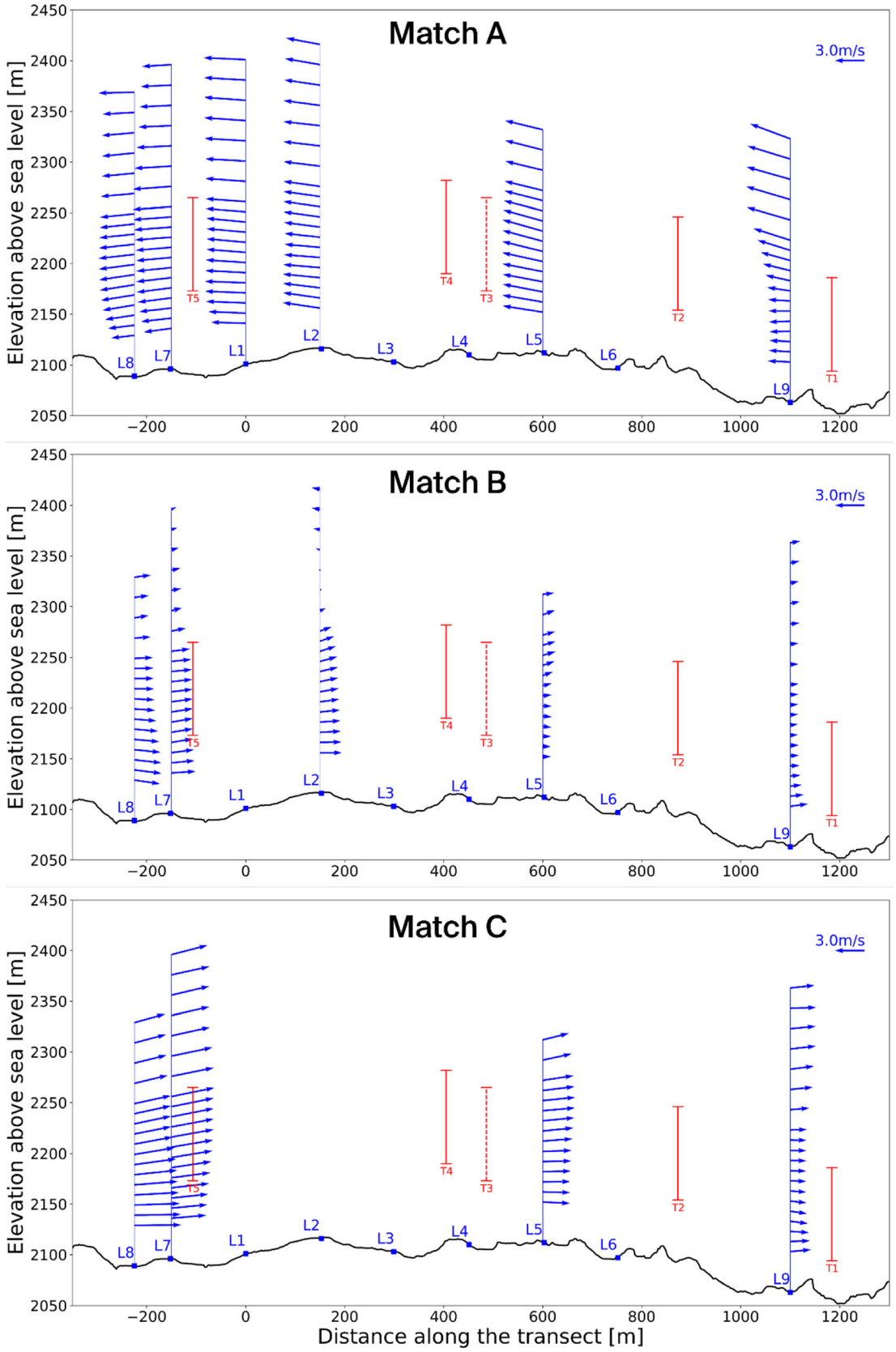

Figure 11. Side view of three characteristic matches on the Gotthard Pass. Turbines in red.

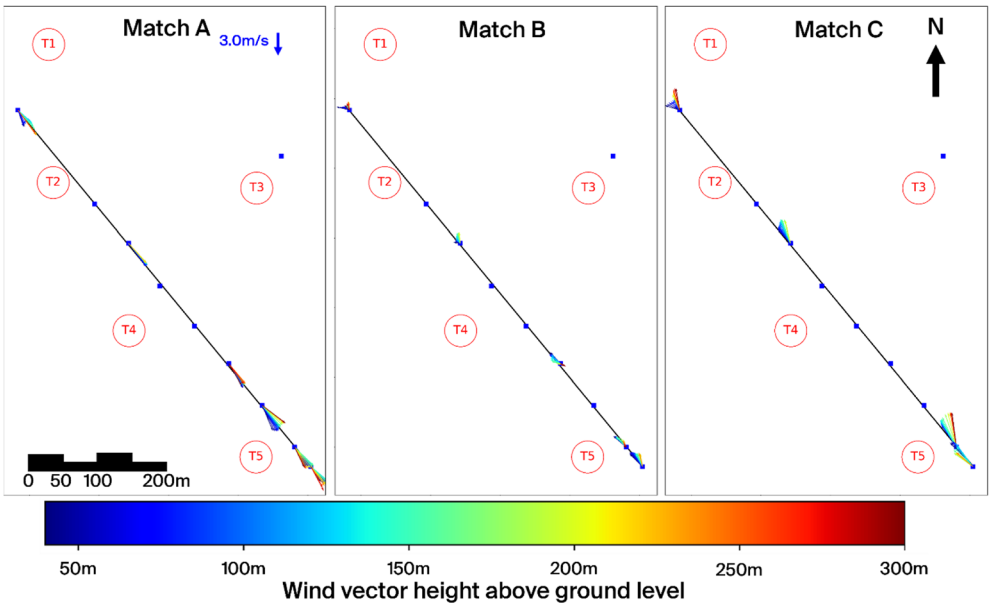

Figure 12. Top view of three characteristic matches on the Gotthard Pass. Turbines in red.

Under idealized conditions in the planetary boundary layer, wind direction is expected to veer with height in the Northern Hemisphere as a result of the Ekman balance between surface friction and the Coriolis force. This Ekman-induced veering typically develops gradually over several hundred meters in the vertical. At L8, however, the observed wind direction changes with height strongly deviate from this classical framework and are instead dominated by local topographic forcing, which overwhelms and distorts the background Ekman veering.

This terrain-induced channelling produces a distinct horizontal veering with height that far exceeds what could be explained by the Coriolis force. Over the 1.5 km length of the Gotthard upper plateau, the maximum deflection by Coriolis would be only about 0.5°, whereas the observed turning is an order of magnitude larger. The separation of air layers around turbine hub height has direct implications for wind turbine performance: Turbines 4 and 5, which interact more with the deflected lower layer, are more strongly affected by veering and shear, while Turbine 3, which is located somewhat higher on the plateau but in the line of topographic prominence, is exposed to strong turbulent flow.

Turbulence kinetic energy

Turbulence kinetic energy (TKE) $k\ [m^2\ s^{-2}]$, described by Equation 6 where $\sigma_v\ [ms^{-1}]$ is the standard deviation of the wind component, exhibits bi-modal distributions where northerly and southerly winds exhibit very different TKE characteristics. This bi-model distribution is similar to the wind speed along the LiDAR transect as shown in Figure 14. In these figures, the red lines represent the probability density functions of the TKE, while the blue vertical lines indicate the mean TKE, allowing for a visual identification of where turbulence is strongest along the transect.

$$k = \frac{1}{2}(\sigma_U^2 + \sigma_V^2 + \sigma_W^2) \tag{6}$$

Table 3. Weibull fit parameters of the Gotthard Wind Park for Northerly and Southerly winds.

Turbine	Northerly wind			Southerly wind		
	k	λ	$\lvert\vec{v}\rvert$	k	λ	$\lvert\vec{v}\rvert$
1	1.31	5.14	4.16	3.53	5.27	4.76
2	1.93	5.31	4.67	3.38	5.38	4.84
3	2.33	6.65	5.75	2.60	6.29	5.52
4	2.54	5.89	5.11	3.03	5.18	4.67
5	2.64	7.66	6.59	2.62	4.80	4.31

Table 4. LiDAR transect metadata of the matches displayed in Figure 11 and Figure 12.

LiDAR location	Match A	Match B	Match C
L1	18:40 19-06-23	-	-
L2	11:50 07-07-23	01:00 11-07-23	-
L3	-	-	-
L4	-	-	-
L5	14:30 31-07-23	06:10 30-07-23	05:30 31-07-23
L6	-	-	-
L7	11:50 24-08-23	01:20 24-08-23	23:00 19-08-23
L8	16:50 02-09-23	02:40 03-09-23	03:20 03-09-23
L9	13:50 10-09-23	02:20 11-09-23	06:00 11-09-23
L10	-	-	-
Wind park wind direction	Northerly	Southerly	Southerly
Global Horizontal Irradiation [Wm^{-2}]	624	13	47
Atmospheric stability [class]	Unstable	Stable	Stable
Vertical shear magnitude [s^{-1}]	0.0068	0.0070	0.0055
Variance of vertical turbulence [m^2s^{-2}]	0.092	0.048	0.029
Synoptic wind speed [ms^{-1}]	8.0	10.2	7.7
Synoptic wind direction [°]	245	277	292
Transect wind speed [ms^{-1}]	9.45	1.48	1.30

For both northerly and southerly winds, the air enters the wind park at low turbulence levels. As the air moves further over the pass, the turbulence kinetic energy gradually increases. This is to be expected as the wind tends to accelerate on the upper plateau due to the increased density of streamlines as the air is pushed over the highest point of the pass and the overall kinetic energy of the wind increases, this will also contribute partly to the increased turbulence kinetic energy. Additionally, the surface obstacles, such as boulders, buildings and wind turbines will partly contribute to the increase of turbulence in the flow. For southerly winds Figure 14b, the increased turbulence in the lee of Turbine 5 can be observed in L1, L2 and L3 around the swept area of the turbine. This effect is not observed for northerly winds, which can be explained by the fact that these LiDAR locations are not directly in the lee of T2 and T4. This is confirmed by the lack of



Figure 13. Indication by the cloud layer of the horizontal stratification for southerly winds due to the Scara Orello mountain (orange).

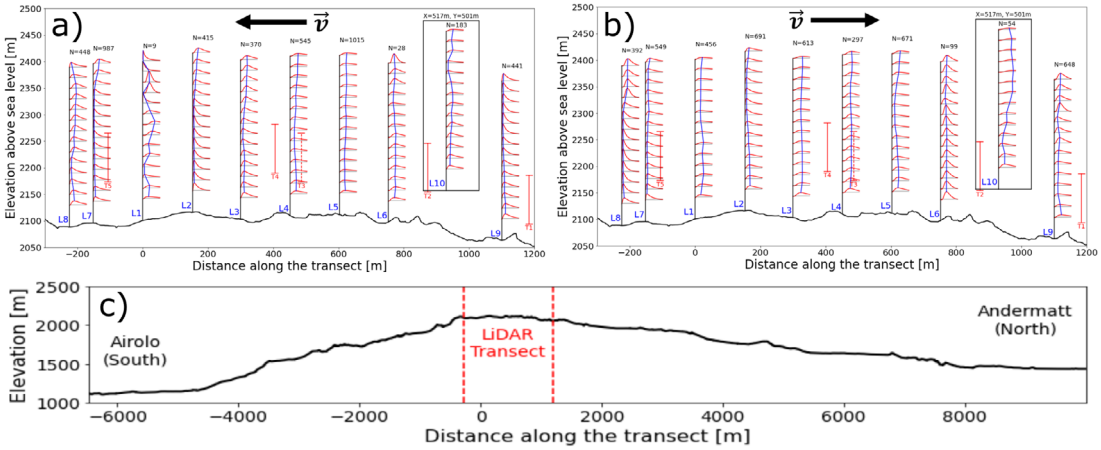

Figure 14. Log-normal fitted TKE PDFs along the Gotthard pass: a) Northerly winds, b) Southerly winds, c) extended elevation profile.

wake effects, typically showing a substantial decrease in wind speed at the elevation of the turbine rotor, observed in these LiDAR profiles.

At measurement L10 the greatest turbulence kinetic energy can be observed for southerly winds. This correlates with the increased southerly wind speeds which were observed during the measurement period at this site. Additionally, the upwind terrain on this side of the pass is notably more complex, with the aforementioned Scara Orello mountain (2242m) obstructing the wind for the western side of the pass. This will likely affect the flow on the eastern pass in a similar way.

We illustrate for the case of a symmetric deviation from a mean wind speed with standard deviation how the effect of non-linearity results in additional power that can be harvested. If we further assume that such a deviation gives the approximate magnitude of the power gain by turbulence, we can estimate the effective energy the turbulence holds for the type E-92 turbine on the Gotthard plateau. Consider the wind turbine power $P(v)$ $[W]$ described by Equation 7:

$$P(v) = \frac{1}{2}\rho A v^3 \tag{7}$$

$\rho = 0.996 \pm 0.021\ kgm^{-3}$ is the air density on the Gotthardpass, $A = \pi r^2 = 6650\ m^2$ the swept area of a wind turbine, $v[m/s]$ the incident wind speed. Since the horizontal standard deviation of the wind for the WindCube is defined by $\sqrt{\sigma_u^2 + \sigma_v^2} = \sigma_{horz}[ms^{-1}]$, we can consider a deviation σ_{horz} above and below the regular wind speed v. Equation 8 provides a first-order estimate of how turbulence around the mean affects turbine power output and can reach up to around 80kW of deviation from the typical wind power curve:

$$P_{turbulence} = \frac{P(v+\sigma_{horz}) + P(v-\sigma_{horz})}{2} - P(v) = \frac{3}{2}\rho A v \sigma_{horz}^2 > 0 \tag{8}$$

The actual effect of turbulence is governed by the curvature of the turbine power curve: In convex sections of the power curve, positive and negative fluctuations are weighted asymmetrically, leading to a net increase in power relative to the mean wind speed. Whereas in concave sections, the reverse occurs and fluctuations produce a net decrease in power. Therefore Equation 8 represents only a rough upper-bound to the influence of turbulence on power production. It does not account for the changing curvature of the real power curve, nor for higher-order asymmetries in the wind speed distribution. For a full quantification, we refer the reader to a work that integrates the measured wind speed probability density function and other vertical variations with the actual turbine power curve as referred to in international standards.[47]

Furthermore, we have validated the assumption of second-order symmetry in the wind speed variations measured the Doppler wind LiDAR. The 1-second wind speed data from the WindCube during the campaign shows that the deviations from the mean are not perfectly normally distributed. They rather remain symmetric up to second order and can be fitted optimally with a Student-t distribution ($\nu = 2.88 \pm 0.02$, $R^2 = 0.996$), which captures the heavy tails observed. From this

the mean horizontal deviation can be expressed as $\sigma_{horz} = \sqrt{v/(v-2)} = 1.81$, Which seems to be independent of height. Which consequently validates that the rough upper-bound still holds.

Regional weather correlations

Subsequently, based on the matching timestamps, the IMIS and SLF stations were assessed in an attempt to find correlations and patterns between the wind on the Gotthard Pass and other atmospheric variables in the vicinity of the pass. These correlations can be of interest in generalising the local high-resolution measurements to nearby locations, enabling an extended domain of the wind energy assessment. Additionally, potential correlations can help in future case studies to characterise specific weather systems from weather models to predict wind profiles around the study area itself.

Regarding the mountainside- and mountaintop-located IMIS stations, which record data at a 1 hour resolution, no strong correlations ($|r| < 0.4$) can be found in any of the atmospheric variables relative to any data collected during the Gotthard 2023 campaign. The mountaintop stations provide moderately better correlations as they better represent the synoptic weather conditions and are less prone to small-scale local topographical effects. A simple model to predict northerly or southerly winds in the Gotthard wind park remains too challenging for simple linear correlation models, however. The mountainside stations generally had worse correlations ($|r| < 0.3$). This is attributed largely to the different slope aspects of the sites where the stations are located, far away from the Gotthard wind park itself.

Finally, the MeteoSwiss weather station Gütsch installed 11 km NNE of the Gotthard wind park, with an elevation of 180 m above the Gotthard wind park on an east-west ridgeline provides the best data for this analysis. Although the wind components measured at Gütsch still lack correlation with those in the Gotthard wind park, barometric pressure, air temperature and humidity strongly correlate with the variables that were measured at Gotthard Pass during the 2023 campaign. Particularly, temperature and pressure can be used to approximate their equivalence on Gotthard when our instruments are not present or had data gaps by using a lapse rate of 6.5°C per km and the barometric equation ($+17.42 \pm 0.36\ hPa$ on Gotthard), respectively. The relative humidity is less correlated to that measured on Gotthard, however, since it is only used for estimating air density on the Gotthard Pass, which is weakly sensitive to relative humidity, we assume the same humidity for both locations. This estimated air density is used to estimate the general turbine efficiency decrease, which can not be attributed to complex terrain interactions in the following section.

Wind turbine efficiency

The bi-directional wind system across the Gotthard is prevalent for the wind shear, wind veer and turbulence on the pass. The compound effects of these combine, and occasionally cancel each other when the air parcels transfer their energy to the wind turbine blades. To study the impact of terrain and flow effects on the efficiency of the five wind turbines, the production power distributions for northerly and southerly winds are shown in Figure 15. Wind speeds are selected between the cut-in speed and the rated wind speed, where the relation $P \propto v^3$ holds. In the range of $4\ ms^{-1} \leq v \leq 10\ ms^{-1}$, small disturbances and perturbations of the flow have the largest impact on power production. The power production is normalised to $7\ ms^{-1}$ by the cubic relation between power and wind speed in this range with Equation 9.

In Figure 15a where only the power data during the measurement campaign is shown, consider the northern Turbines 1 and 2. The southerly winds are more efficient at transferring energy to the wind turbine than their northerly counterparts.

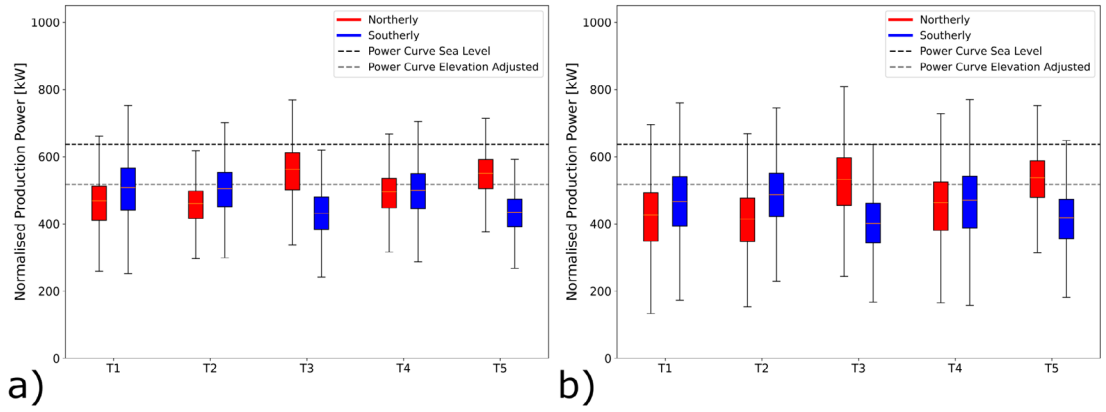

Figure 15. Power generated by turbine and wind directions. (**a**) summer campaign period (19 June 2023 – 20 September 2023), (**b**) the entire dataset (October 2020 – September 2023).

This discrepancy can be explained partly by the increased turbulence intensity as the wind moves over the upper plateau before it reaches these turbines. For the northerly winds there is still a significant vertical wind speed component incident on the turbines increasing blade stresses and, making the programmed angle of attack of the turbine blades less efficient.

$$P_{normalised} = P(v)\frac{C_p(7ms^{-1})(7ms^{-1})^3}{C_p(v)v^3}, 4ms^{-1} \leq v \leq 10ms^{-1} \quad (9)$$

Remaining in Figure 15a, the central Turbine 4 generally experiences the benefits of the northerly and southerly winds equally with very low turbulence for both directions as well as moderate wind shear and veer only slightly reducing the turbine efficiency. Vertical wind components play almost no role for this turbine.

The most interesting sites are Turbines 5 and 3 during the campaign period, shown in Figure 15a. These turbines not only benefit from flow acceleration for northerly winds, which generally bring higher wind speeds to this part of the pass. Remarkably, they can also transfer this energy more efficiently than expected when referring to the manufacturer's power curve when corrected for the reduced air density on the Gotthard Pass as a result of the elevation. This apparent out-performance can be explained by the increased turbulence which reduces the average wind speeds to lower and unrealistic values due to the limitations of the nacelle-mounted anemometer, whilst the kinetic energy of the wind is higher than indicated. These effects are exaggerated most for the strong northerly winds which accelerate to much greater wind speeds before reaching these turbines due to the linear scaling with the average wind speed v, as shown by Equation 8. The wind shear and wind veer for these northerly winds are already reduced to a minimum as observed for southerly winds for Turbines 1 and 2, and thus do not decrease the performance. Meanwhile, the strong shear and veer for southerly winds, as observed in Match B and C, which has a detrimental effect on the power production. We do not observe the same apparent increase in power output due to turbulence for the northern Turbines 1 and 2, as the wind speeds and turbulence are generally lower.

During snow-covered periods, which are not included in our LiDAR measurement period, but are partly represented in the longer time domain of Figure 15b, a general decrease in efficiency is observed over all the turbines. In addition to surface-related and atmospheric effects, blade icing during snow-covered periods may further reduce aerodynamic efficiency and contribute to the observed performance decrease. While icing is not explicitly quantified in this study, it is a known factor affecting turbine performance in high-alpine winter conditions. This can likely be explained by the multiple meters thick snow layer covering the mountain pass for 7 months per year smoothing out the terrain, reducing the apparent power increase by turbulence. The effect of the smoother surface which increases wind speeds is filtered out by the power normalisation in Equation 9. The high performance of Turbines 3 and 5 is therefore reduced the greatest amount for northerlies, as they experienced the greatest discrepancies in power production in summer time. There may be additional factors such as the presence of a stable atmospheric boundary layer due to the greatly reduced turbulent heat flux over the snow, resulting in more vertically stratified wind profiles that show more shear and veer and less turbulent airflow incident on the turbines. We refer the reader to continuation work on this topic.[49]

Sequential LiDAR vs synchronised LiDAR

The sequential and synchronised LiDAR methods are both designed to reconstruct three-dimensional wind fields, but they differ considerably in logistics, costs, and data quality. The sequential method requires only a single LiDAR, making equipment costs relatively low. However, this approach demands regular relocation of the instrument, which increases personnel time and logistical complexity. By contrast, synchronised methods use two or more LiDARs operating in parallel. These require extensive pre-campaign planning, advanced expertise in operating multiple instruments, and more involved post-processing to merge datasets into a consistent wind field.

The sequential approach is therefore simpler to deploy and requires less upfront planning, though it relies more heavily on numerical modelling (e.g. flow field simulations) to reconstruct missing flow structures. Such expertise is increasingly common in the commercial wind energy sector, making sequential methods more accessible. Synchronised LiDARs, on the other hand, can achieve higher spatial resolution and cover larger domains by combining measurements from multiple instruments. Their performance is still constrained by the laser stare-time needed to collect enough return photons, but modern systems can capture up to 300 unique points in a 10-min averaging period, the standard in wind energy assessment. For the 20 range gates used in this study, a three-LiDAR synchronised system could effectively reproduce a transect equivalent to 15 sequential profiles, while providing much higher data availability since no matching algorithm is required.[50]

Conclusion

This work presents a novel method for high-resolution three-dimensional wind profile measurements in channelized flow conditions within complex terrain using a sequential spatially distributed LiDAR deployment. The project took place in the Gotthard wind park during the summer of 2023. The sequential LiDAR deployment is made along a transect on the western side of the upper plateau of the Gotthard Pass at an elevation of around 2100 m a.s.l., using a profiling VAISALA WindCube V2.1 wind-Doppler LiDAR instrument. The transect of nine sequential LiDAR locations and an additional tenth deployment on the eastern side of the pass aims to probe the entire wind park closely following the sites of five Enercon E92 wind turbines, constituting the high alpine Gotthard wind park. The Gotthard Pass is located in the centre of the Alps and features many topographical effects and flow features typical of complex terrain that influence the wind profile that is incident on the wind turbines and which also can affect the performance of the latter. It is one of the few alpine passes that experiences both northerly and southerly Föhn winds, and wind channelling and acceleration over the pass can be seen from the measured sequential LiDAR wind profiles.

A matching algorithm is proposed to allow for inter-comparison of LiDAR wind profiles measured at different moments in time, but for similar incoming wind conditions, verified by the meteorological observations on the nacelles of the five turbines and typical atmospheric parameters derived from simulations of the atmosphere. Using eight characteristic features from the HICAR v1.1 model and applying strict standard deviation thresholds, we substantially refine the nacelle-based matching approach. This filtering reduces the total number and size of matches but ensures that the retained combinations represent wind profiles that are coherent not only in terms of turbine nacelle wind speed, but also in radiation, stability, shear, turbulence, and both transect-scale and synoptic flow. Although matches are fewer after filtering, their robustness is greatly enhanced, providing higher confidence that the selected profiles capture consistent inflow and atmospheric conditions across the Gotthard wind park. This matching algorithm is successful in identifying a substantial number of similar wind profiles throughout the three-month field campaign, with a maximum of six wind profiles measured at different locations, which are capable of describing the typical winds observed on the Gotthard pass.

The sequential LiDAR data provides a unique visualisation of wind shear and wind veer along the alpine pass, as well as turbulence profiles clearly illustrating the complex terrain influences that impact wind turbine performance in mountainous applications (Sections 3, 5). We provide a qualitative overview of the complex terrain effects that significantly influence wind turbine performance, both in terms of potential drawbacks and benefits. Particularly, the stronger northerly winds exhibit acceleration over the pass, increasing wind energy production greatly for turbines furthest downwind. For upwind turbines, wind veer and shear decrease turbine performance, but this effect is reduced further downwind, where the channelling of the narrow pass plateau reduces these effects. The turbulence is largest on the eastern side of the pass, independent of the wind direction, which can be partly explained by the local terrain being rougher compared to the western part of the plateau. The presence of turbulence causes an apparent increase in wind turbine efficiency, which can actually be attributed to kinetic energy in the wind being transferred to turbulence instead of the average wind flow. The nacelle mounted anemometer only measures the average wind speed, but misses out on the short-term wind speed deviations which have a non-linear positive effect on the energy production of the turbines. A qualitative assessment of the compound effects of complex terrain on the incident wind agrees well with the turbine data. The applicability of the presented approach may be reduced at exposed hilltop or ridge locations, where strong flow inclination and separation can violate the homogeneity assumptions required for ground-based Doppler LiDAR measurements.

We hypothesise that a terrain surface smooth by snow during the 7 month long snow-covered winter period reduces turbulence, which is supported by observations from nacelle-mounted anemometers. In future work, we plan to explore in more detail the effect of the presence of a smooth snow pack, which covers the wind park for 7 months of the year. Secondly, more complex interactions between air density and atmospheric stability outside of the summer period, and how this influences wind turbine performance will be tested. The current measurements in the region lack consistent and reliable atmospheric variables, requiring improved sensor coverage for this purpose. The sequential LiDAR measurement technique is an excellent candidate to improve wind profile characterization in channelized wind sites within complex terrain, where flow alignment and limited separation support the underlying LiDAR measurement assumptions.

Ethics and consent

Ethical approval and consent were not required.

Data availability

All data collected during the Gotthard experimental campaign are publicly available via Zenodo: Sequential Wind-Doppler LiDAR wind profile measurements on the Gotthard pass in Switzerland – Summer 2023, DOI: 10.5281/zenodo.14524723.[52]

This project contains the following underlying data: Wind-Doppler LiDAR measurements along the transect in the Gotthard Wind Park.

This project contains the following underlying data:

- Gotthard_Transect_Experiment_STA_standard_Final.nc
- Opening_netCDF_4_formats.docx

Data are available under the terms of theCreative Commons Attribution 4.0 International.

The authors have extracted weather data from MeteoSwiss and WSL SLF IMIS weather stations which are available upon request to the respective institutions. The wind turbine data made available by Azienda Elettrica Ticinise[51] was shared with the authors under non-disclosure agreement for this research project.

One dataset that was used in our study has time-series data of wind power, wind speed and control algorithms of the wind turbines. This data was disclosed to the laboratory only under NDA. Readers, with interest for this data, can make a special request to the corresponding author after which the company will consider whether they will share this data under similar NDA conditions.

The HICAR v1.1 simulations made to complement the measurements is too large to share and are made available upon request to the corresponding author.

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✓ **Baoyuan Deng**
Hunan University, Changsha, China

I'm leaning toward accepting this paper.
Honestly, I think the authors have done a solid job addressing the big concerns from earlier rounds. The idea itself is pretty cool — instead of needing three expensive LiDARs running at the same time, they show you can get similar results with just one, moved around strategically. That's a big deal for remote alpine sites.
Why I'm okay with this paper in its present format:
1) They fixed the matching logic. They've added eight different checks using their CFD model (HICAR). It's not perfect, but it's way more rigorous than before.
2) They're honest about the limits. They're not claiming this works everywhere. They clearly say it's best for "channelized" valleys and won't work on super exposed ridges.
3) Real-world relevance. The Gotthard Pass case study actually tells us something useful: how northerly vs. southerly winds mess with turbine efficiency in different ways.
What still bugs me a tiny bit (but not enough to reject):
1) Winter is missing. Seven months of the year, that place is buried in snow, which totally changes the wind. no dataset is ever perfect, and they admit this gap openly. Besides, the collected data is open-sourced in zenodo.
2) HICAR could use more checking. They didn't do a deep dive comparing the model directly to measurements, but for the purpose of filtering matches, it seems to do the job.
This paper isn't a flawless, ready-for-prime-time industrial tool yet. But as a smart, creative approach to studying complex terrain? Definitely worth indexing.
I recommend to accept this paper.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: lidar, wind turbine, data processing

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 07 April 2026

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Feng Guo
Shanghai Jiao Tong University, Dongchuan Road, Shanghai, China

The authors have adequately addressed my review concerns, and I now support the manuscript for indexing.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Wind resource assessment, wind lidar, wind turbine aero-elastic

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 31 March 2026

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Shengming Tang
Shanghai Typhoon Institute of China Meteorological Administration, Shanghai, China

I am satisfied with the author responses and have no further questions or comments.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Boundary layer meteorology

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 2

Reviewer Report 10 February 2026

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Norman Wildmann
Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany

Van Schaik et al. present an experimental study which utilizes one lidar of type Windcube v2.1 to measure wind profiles at an Alpine pass at different locations. The topic is relevant, since complex terrain flow effects are critical for wind energy siting and many uncertainties remain. In the revised manuscript the authors have included long-term CFD simulations, which I think is absolutely crucial to understand the flow in such complex terrain and interpret the lidar measurements. Filtering the matching situations further with more criteria is a step in the right direction, but I still do not believe that the matching of sequential liar periods is appropriate. I agree with reviewer Nicolas Angelou that there are too many uncertainties in the flow complexity and the lidar measurements in complex terrain to trust the matched data. The manuscript gives a wrong impression that it could be a sound method to combine spatially and temporally separated measurements in complex terrain for site assessment. A few more general comments are given below. The focus of the analyses would have to be significantly changed in my opinion to justify indexing. I recommend to reject the manuscript.

General comments:

- I cannot find a response to my initial review. I only find responses to Nicolas Angelou and Shengming Tang. I can thus not fully comprehend if my initial review was incorporated into the revision.
- I miss an evaluation of the HICAR simulations. How do the statistics from those simulations compare to measurements on site? Which features can be captured and which cannot with the given resolution? The lidar and in situ data could maybe be used to evaluate this, which would make a much more relevant and scientifically sound study.
- The general research questions and approaches remain very questionable. In the end 35 matches remain for a multi-lidar flow evaluation under different conditions. For site assessment, this is not really suitable.
- I thus disagree with the last statement: "The sequential LiDAR measurement technique is an excellent candidate to improve wind profile data in the complex terrain without a large amount of meteorological equipment." I think the dataset is a very good candidate for case-study based evaluation of models and development of lidar wind retrievals in complex terrain and should be used and advertised as such.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: boundary-layer meteorology, lidar measurements, complex terrain, wind energy

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

Author Response 13 Feb 2026

Brandon van Schaik

We regret to hear that the reviewer was unable to read our responses to the previous comments. Please find the comments below for your convience: Norman Wildmann - It should be made more clear in the introduction what the actual goal is of the measurements. You could describe what is the standard procedure for WEA, how long the requirements are for instrument deployment and statistics of wind sectors t benchmark your results with. If wind resource assessment is the goal, than I get the impression that the database is much too small and the sequential lidar transects fails to provide the necessary information. If the goal is to study specific flow conditions, I would expect more of a focus on specific situations and some numerical simulations to accompany the measurements. The section title of Methods was misplaced in this draft which meant that a large part of the introduction was actually displayed as the start of the introduction. We have indicated this to be changed to the correct position in the next iteration. Regarding the clearity of the goals, it is **addressed in the manuscript as such:** “This work serves as a proof of concept and as a preliminary showcase of the unique data sets and analyses that are unlocked by the sequential LiDAR experimental methodology, enabling the high-resolution study of the three-dimensional wind over the entire wind park domain.”. In response to this comment, and those made by another reviewer, we have complemented the LiDAR observations with additional CFD simulations covering the full 3-month campaign period and the entire

mountain pass. These simulations provide spatially and temporally continuous wind fields that support the short-term measurements. Specifically, we have identified 8 characteristic features including, global horizontal irradiance, atmospheric stability, vertical shear magnitude, variance of the vertical turbulence, an average of the transect wind field, and the synoptic wind at 5km. To this end, the Methodology section is completely overhauled and Results updated accordingly. We believe this addresses the reviewer's concern by providing a more complete picture of the wind conditions across all sites.
- The experimental setup is flawed from my perspective because there is no reference to benchmark the results with. I think it would have been important to have at least one lidar continuously at one position. A CFD model to simulate specific wind conditions and check if matching different situations is appropriate could also be applied, but is not provided. Atmospheric stability is not measured at all, but is crucial. Thanks to your suggestions we have opted to provide additional CFD simulations to help contextualize the turbine wind vector matching algorithm. We have updated the matching algorithm as elaborated in the previous comments. We refer to the Methodology section of the manuscript for the detailed overview of the 8 characteristic features that are now implemented.
- The method section is not well introduced and the purpose for the whole wind speed matching remains very unclear when it is first introduced and is not well explained. The equations are unprecise and variable names are not well introduced. To make this transition to the Methodology more clear, as well as to introduce the idea of the wind speed matching immediately, we have moved the LiDAR details to the instrumentation section. We have improved equations and variables and completely overhauled the Methodology section to include the 8 CFD characteristic features. We believe this overhaul has greatly improved the flow of this section.
- The way I understand the matching algorithm, two situations are considered the same if wind vectors are within a certain margin, but that is not a full description of the flow. We have updated the matching algorithm as elaborated in the previous comments. We refer to the Methodology section of the manuscript for the detailed overview of the 8 characteristic features that are now implemented. - Figures are of bad quality (low resolution). The captions are not describing the figures well. Figure quality has been addressed. We are limited to 15 words per caption by the journal, we have optimised captions within this limit.
- Equations are not well explained and variables not described. We have checked all equations and verified that variables are introduced and described.
- The structure of the manuscript is not consistent jumping back and forth between methods, results, definition of goals. There is no clear story-line. We have updated the matching algorithm as elaborated in the previous comments. We refer to the Methodology section of the manuscript for the detailed overview of the 8 characteristic features that are now implemented.
- Many statements and references are unprecise and sometimes even wrong. The authors should carefully revise the text. We assume said statements and references are described in the reviewer's specific comments. We have addressed those below.
- Drawing conclusions from wind profiles that are put together from different days and conditions, just matched by wind speed at hub height can be extremely misleading. We have updated the matching algorithm as elaborated in the previous comments. We refer to the Methodology section of the manuscript for the detailed overview of the 8 characteristic features that are now implemented.
- The manuscript is provided in a format which is hard to review (2 columns, no line

numbers, etc.). That is maybe not the authors fault, but editors should consider to change the format. We thank the reviewer for pointing this out. The manuscript format is determined by the journal's submission system, and unfortunately we do not have direct control over line numbering or layout. We trust that the editorial office will take this into consideration.
Specific comments:
p.4, paragraph 1: There are clear definitions for terrain complexity in the IEC 61400. It is probably good to elude a bit on that in the introduction and make clear that the complexity in this study is of the highest complexity (I assume)
We appreciate the reviewer's suggestion. While the IEC 61400 provides clear definitions for terrain complexity, it is not an open-access document, and therefore we have chosen not to cite it directly. Nonetheless, we agree that the terrain in our study area qualifies as highly complex according to commonly used classifications. We have clarified this in the revised introduction to better frame the context of our work, without relying on proprietary standards. **Addressed in the manuscript as such:** "The Gotthard Wind Park can be categorised as the highest degree of complex terrain for wind energy development, characterised by large elevation changes, up- and downwind valleys and steep escarpments within the wind park itself." p.4, paragraph 1: "influencing the performance of wind turbines by reducing or augmenting their efficiency". That sentence is not giving much information
Addressed in the manuscript as such: "influencing the performance of the wind turbine by the non-idealised wind flow into the turbine." p.4, 2nd column 2nd paragraph: "airborne lidar" - that is not correct. There was no airborne lidar measuring wind transects across the valley at Perdigao. We thank the reviewer for catching this mistake. The reference to "airborne lidar" was incorrect and has been removed. It was a confusion with the airborne surface scanning LiDAR used at Perdigão. p.4, 2nd column 2nd paragraph: simulations cannot prove the validity of lidar measurements and were not used for that purpose in the referenced studies. **Addressed in the manuscript as such:** "establishing the use of LiDAR measurements as a valid wind assessment tool over a wide range of spatial resolutions." p.4, 2nd column 3rd paragraph: WEAs operate lidars to perform WEA? that is a weird construction
"WEAs rarely operate more than one LiDAR to perform a wind energy assessment."
Replaced by: "WEA studies rarely operate more than one LiDAR" p.7, 2nd column "Lidar details": The range gate increments was already introduced in the chapter before. It may make sense to move this section before the explanation of the sequential Instrumentation overview.
Thank you for the helpful suggestion, we have adopted this in the revision. p.9, 1st column, 2nd paragraph: why is the temperature sensor at 1m? Usually 2m is a standardized height for such measurements.
Out of practical reasons this was done. A one metre rebar pole could be easily hammered into the soil. Longer poles to mount the sensor at 2m would require guywires which was not always possible in the terrain. Since the LiDAR was moved every week, this was not practical. Since the surface topography is free of brushes and rocks, this difference should not impact the variances in the temperature readings much. Particularly since we average over 10min intervals. Since the temperature is only used for air density calculations in which the temperature only has a small sensitivity, we do not see a reason to distrust the accuracy of this data. **Addressed in the manuscript as such:** "A radiation-shielded combined pressure, temperature, and humidity sensor was placed near the LiDAR 1 m above the ground which

is solely used to calculate the local air density." p.9, Eq.1 etc.: At this point in the manuscript it is unclear why you want to calculate the difference of all 10-minute wind speeds for the five turbines
With the additional CFD simulations methods in the manuscript, this has been addressed accordingly. We have also introduced the goals more clearly, and earlier in the manuscript. p.10, Fig.6: the resolution of this figure is very low and texts are hard to read.
All figures have been replaced with higher-resolution versions in the revised manuscript. In addition, Figure 6 is no longer included, as it became irrelevant following the revisions to the Methodology section and has been removed. p.11, right column, 2nd paragraph: pressure, temperature and humidity are not shown in this manuscript though, right? Which instrumentation is used to check it? Are there any measures for stability? How the flow develops along the transect is surely dependent on stability.
We only use pressure temperature and humidity to calculate the average air density over the whole campaign. We mention the existence of this sensor as it is included in the data set that is co-published with this paper. The sensor in use is the standard PTH sensor provided by VAISALA for the WindCube v2.1. More details are now given in the instrumentation table (Table 1). Atmospheric stability is now addressed with CFD simulations. We refer the reviewer to our reply of his first comment as well as the Methodology section of the revised manuscript for the full details. p.11, right column, "Results": are Fig.6&7 not already results? These figure have become irrelevant following the revisions to the Methodology section and have since been removed. p.11, right column, last paragraphs: why are these paragraphs italic? where do they belong to?
We thank the reviewer for noting this editing error. The paragraphs are now placed correctly in the revised manuscript. p.13, Table 3: why not show the distributions?
In our view, the distributions are not directly relevant to the goals of the study. Presenting the results in tabular form provides a more space-efficient and quantitative summary, allowing readers to readily compare the two wind directions as well as reproduce/refer to the data immediately. p.11, "above rated wind speed": the wind roses do not distinguish between above and below rated wind speed, the upper bin is >8m/s, but rated wind speed is 11m/s.
Excellent suggestion, the wind roses are updated to reflect the different stages in the E-92 power curve, and the figure has been updated. p.12, Figure 8: What are turbines A-E? So far they were referenced with numbers 1-5 or T1-T5. Please be consistent or describe in the caption.
Combined with the previous comment, we have adapted this as well in the figure. p.13, Figure 9: The caption should be more descriptive about what the colors and arrows mean.
We are limited to 15 words per figure/table caption by the journal regulations. We have described this in more detail in the text. We have also added a legend to explain the difference in colours. Besides, this figure has been replaced due to the improved methodology as suggested in your earlier comments. We refer the reviewer to the Transect wind profile evolution and Wind shear and veer subsections in the results for our improved results. p.13, right column, first paragraph: If you see a flow acceleration between the position, how can you be sure that acceleration effects are not also present at hub height and would this not be a problem for the wind matching? You actually match conditions which are very different. We have updated the matching algorithm as elaborated in the previous comments. We refer to the Methodology section of the manuscript for the detailed overview of the 8 characteristic features that are now implemented. This flow acceleration

can now be identified using by CFD simulation characteristic features: “Vertical shear magnitude”, “Variance of the vertical turbulence”, and “Transect-averaged wind”. We refer the reviewer to the Transect wind profile evolution and Wind shear and veer subsections in the results for our improved results.
p.14, Figure 11: The figure clearly shows that for positions L4 and L8 there was strong shear and veer, thus a very different flow condition than for the other positions. How can you put these conditions together? It does not make sense.
We have updated the matching algorithm as elaborated in the previous comments. We refer to the Methodology section of the manuscript for the detailed overview of the 8 characteristic features that are now implemented. This shear/veer concern can now be identified using by CFD simulation characteristic features: “Vertical shear magnitude”, “Variance of the vertical turbulence”, “Global Horizontal Irradiance”, “Atmospheric stability”, and “Synoptic wind at 5km”. We refer the reviewer to the Transect wind profile evolution and Wind shear and veer subsections in the results for our improved results. p.14, right column, last paragraph: I cannot believe that the shear and veer at a specific location is independent of atmospheric stability.
We have updated the matching algorithm as elaborated in the previous comments. We refer to the Methodology section of the manuscript for the detailed overview of the 8 characteristic features that are now implemented. This shear/veer and atmospheric stability concern can now be identified using by CFD simulation characteristic features: “Vertical shear magnitude”, “Variance of the vertical turbulence”, and “Atmospheric stability”. We refer the reviewer to the Transect wind profile evolution and Wind shear and veer subsections in the results for our improved results. p.15, Table 4: the table shows that wind profiles of early morning, early afternoon and late afternoon are mixed.
We have updated the matching algorithm as elaborated in the previous comments. We refer to the Methodology section of the manuscript for the detailed overview of the 8 characteristic features that are now implemented. This time of day mixing can now be identified using by CFD simulation characteristic features: “Global Horizontal Irradiance”, and “Atmospheric Stability” We have consequently updated the table to address the stricter matching protocol discussed in the overhauled Methodology section. p.17, Fig.14: what are the axis of those TKE distribution plots?
We have revised the captions to clarify that the plots represent probability density functions of the TKE. The as the exact values of TKE are not directly relevant for our conclusions, and for clarity we therefore choose to not include x ticks or y ticks. Since our caption size is limited, we have updated the manuscript section in which the figure is first referred to as shown below. The plots are intended to highlight relative differences, and since all TKE distributions share identical x-limits, they can be visually intercompared as discussed in the manuscript. **Addressed in the manuscript as such:** “This bi-model distribution is similar to the wind speed, along the LiDAR transect as shown in Figure 12. In these figures, the red lines represent the probability density functions of the TKE, while the blue vertical lines indicate the mean TKE, allowing for a visual identification of where turbulence is strongest along the transect.” p.16, "Turbulence kinetic energy": This Section is premature. You cannot make statistics of TKE with this database and calculate effects on power production the way it is done here. The references are wrong too. Reference 8 does not provide Eq. 8. I recommend to have a close look at the IEC 61400 standards.
We thank the reviewer for this valuable comment. We have revised the section to clarify that our analysis is not intended as a full turbulence kinetic energy (TKE) assessment, but rather

as a simplified approach to provide a rough upper bound on the potential influence of turbulence on turbine performance. We now emphasize that Eq. (8) is a first-order approximation based on the curvature of the power curve and assumes symmetric fluctuations up to second order. Furthermore, we have verified the applicability of Eq. (8) using our 1-second LiDAR data, which shows that the deviations from the mean are approximately symmetric and can be fitted by a Student-t distribution. This supports the use of Eq. (8) as a conservative upper-bound rather than a precise quantification. Finally, we have corrected the references and added a note pointing the reader to the IEC 61400 standards, which provide the proper framework for turbulence intensity and load assessments. **Addressed in the manuscript as such:** "Equation 8 provides a first-order estimate of how turbulence around the mean affect turbine power output: Equation 8 *P turbulence=Pv+σhorz+Pv-σhorz2-Pv=32ρ A v σhorz2>0*

$P_{turbulence} = \frac{P(v+\sigma_{horz})+P(v-\sigma_{horz})}{2} - P(v) = \frac{3}{2}\rho A v \sigma_{horz}^2 > 0$ However, the actual effect of turbulence is governed by the curvature of the turbine power curve: In convex sections of the power curve, positive and negative fluctuations are weighted asymmetrically, leading to a net increase in power relative to the mean wind speed. Whereas in concave sections, the reverse occurs and fluctuations produce a net decrease in power. Therefore Equation 8 represents only a rough upper-bound to the influence of turbulence on power production. It does not account for the changing curvature of the real power curve, nor for higher-order asymmetries in the wind speed distribution. For a full quantification, we refer the reader to a work that integrates the measured wind speed probability density function and other vertical variations with the actual turbine power curve as referred to in international standards. Furthermore, we have validated the assumption of second-order symmetry in the wind speed variations measured the Doppler wind LiDAR. The 1-second wind speed data from the WindCube during the campaign shows that the deviations from the mean are not perfectly normally distributed. They rather remain symmetric up to second order and an be fitted optimally with a Student-t distribution (*v*=2.88±0.02, *R*2=0.996

$v = 2.88 \pm 0.02, R^2 = 0.996$), which captures the heavy tails observed. From this the mean horizontal deviation can be expressed as *σhorz=v/*(*v*-2) =1.81

$\sigma_{horz} = \sqrt{v/(v-2)} = 1.81$, Which seems to be independent of height. Which consequently validates that the rough upper-bound still holds." p.19, Fig.15: What is the normalized power production. There should be an equation somewhere.
Addressed in the manuscript as such: "The power production is normalised to 7 ms^(-1) 7 m/s by the cubic relation between power and wind speed in this range with Equation 9. Equation 9 *Pnormalised=PvCp(7ms-1)7 ms-13Cp(v)v3, 4 ms-1*≤v≤10 m*s-1*

$P_{normalised} = P(v)\frac{C_p(7ms^{-1})(7\ ms^{-1})^3}{C_p(v)v^3}, 4\ ms^{-1} \le v \le 10\ ms^{-1}$ " p.19, "Sequential vs. Synchronized": This section does not give any new information compared to the introduction and an actual comparison cannot be made, because data from synchronized lidars is not available in this campaign.
We have conducted additional CFD simulations to address this concern, as outlined in our earlier responses. We believe that these methodological adaptations improve the robustness of the results and provide sufficient support for our conclusions in this section.

p.19, "Conclusion": "a novel method for high-resolution, three-dimensional wind profile measurements" - I disagree. The data presented here is not "high-resolution three-dimensional" It is standard wind profiles with Windcube v2.1. for short time periods at different locations.
We thank the reviewer for this comment. While we agree that standard WindCube v2.1 instruments provide vertical wind profiles at single locations, our methodology goes beyond this typical use. By deploying the lidar sequentially along a dense transect with 150 m horizontal spacing and 10–20 m vertical resolution, we obtain a high-resolution, three-dimensional reconstruction of the wind field across complex terrain. Something that cannot be achieved with a single lidar in a fixed location. Furthermore, the newly added CFD simulations now support and address the reviewer's concerns about temporal discontinuity and the matching algorithm. Therefore, we believe that the description of the method as "high-resolution, three-dimensional wind profile measurements" is appropriate in the context of this study. p.20, second paragraph: I disagree that the matching algorithm is successful. The analyses show that just matching the wind speed at hub height is not enough to describe a common flow situation in such complex environment. Actually it is misleading to suggest it does. The newly added CFD simulations help address the reviewer's concerns regarding temporal discontinuity and provide validation for the adapted matching algorithm. We therefore consider the revised algorithm to be appropriate and effective for the purposes of this study.

Competing Interests: No competing interests were disclosed.

Reviewer Report 21 January 2026

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Nikolas Angelou
Technical University of Dermark (DTU), Frederiksborgvej, Denmark

I would like to thank the authors for their thorough responses to the questions and comments raised in the first version of this manuscript. The revised paper is well-structured, and I appreciate the detailed explanation of the methodology as well as the additional effort to strengthen the analysis through 3D simulations of the wind field.
However, despite these positive aspects, I think there remain some fundamental weaknesses in the study.
Specific comments:

1. The proposed method for matching wind profiles obtained from wind lidar profilers relies on reference measurements (in the initial manuscript) and, in the revised version, on reference measurements and CFD data. This raises concerns about the applicability of the method for wind resource assessment, as it requires pre-existing wind turbines and

additionally, the accuracy of CFD simulations in complex terrain is uncertain. Furthermore, in the updated manuscript, where CFD data are used, there is no explanation of the rationale behind the selection of the eight parameters used.

2. The accuracy of ground-based wind lidar profilers in measuring mean wind speed depends on the assumption of spatial flow homogeneity. In the revised manuscript, CFD data are used to support the hypothesis that the flow distortion at the locations where the wind lidar profiler was installed, is minimal. However, this conclusion depends on the reliability of the CFD simulation. Furthermore, even if this assumption holds for the specific site studied, flows in complex terrain are inherently inhomogeneous. Inhomogeneities that are even stronger when the lidar's measurement volume includes turbine wakes (as the case for example of the L9 profile in Figure 11). This will introduce a bias in estimating the mean wind vector and would have an even greater impact on the accuracy of second-order moments derived from lidar measurements.
3. The authors state that their intent is not to present a climatological analysis but to investigate spatial flow variability. However, it is unclear how spatial variability can be decoupled from temporal variability. While CFD simulations could provide insight, this would require validation demonstrating the model's accuracy in predicting wind profiles for the complex terrain under study.
4. In the section *"Gotthard sequential LIDAR transect experiment"*, it is stated that HICAR "can resolve terrain-induced flow features at the hectometer scale." Later, in *"Instrumentation overview"*, the resolution is given as 50 m for the HICAR v1.1 model. Regardless of which value is correct, I am concerned whether this spatial resolution is sufficient to estimate the expected bias in mean wind speed caused by spatial inhomogeneities.
5. In the section *"LIDAR details"*, the manuscript mentions "five pulsed laser beams, which are magnetically controlled by the instrument." Could the authors clarify what is meant by "magnetically controlled"? Additionally, the text states that the "return signal... 30 mW mean power laser is recaptured." Is this accurate?

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Wind Lidar, Wind Energy, Atmospheric Boundary Layer

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

Author Response 30 Jan 2026

Brandon van Schaik

IMPORTANT NOTE: Your review was received after resubmission of the manuscript. Due to the current system, we are unable to resubmit the changes yet until the latest version is online. Since we have had the time to address your comments below, we believe it is better to already reply to you. If you provide us your e-mail we can send you the updated manuscript with track changes for validation. We apologize for this inconvenience but it is out of our hands as authors. Nikolas Angelou I would like to thank the authors for their thorough responses to the questions and comments raised in the first version of this manuscript. The revised paper is well-structured, and I appreciate the detailed explanation

of the methodology as well as the additional effort to strengthen the analysis through 3D simulations of the wind field. However, despite these positive aspects, I think there remain some fundamental weaknesses in the study. We would like to thank you for your second review of our manuscript. Before answering the specific comments below, it is important to note that we have already submitted a third version including the comments of reviewers Shengming Tang and Feng Guo, which was probably not available to you yet at the point of your review. We will therefore submit a fourth version building on that version, rather than the version you have considered. A few changes have already been made based on the other reviewers' comments. **Specific comments:**

1. The proposed method for matching wind profiles obtained from wind lidar profilers relies on reference measurements (in the initial manuscript) and, in the revised version, on reference measurements and CFD data. This raises concerns about the applicability of the method for wind resource assessment, as it requires pre-existing wind turbines and additionally, the accuracy of CFD simulations in complex terrain is uncertain. Furthermore, in the updated manuscript, where CFD data are used, there is no explanation of the rationale behind the selection of the eight parameters used.

The inclusion of CFD simulations in the revised manuscript was made in direct response to requests from the reviewers (Norman Wildmann and yourself) in the previous review round, who suggested that reference data beyond in situ measurements would strengthen the methodological framework. We therefore find it important to clarify that the current formulation of the method does not rely on CFD simulations as a replacement for measurements, nor does it assume that CFD can accurately reproduce instantaneous wind profiles in complex terrain. On the contrary, one of the key findings of this study is that CFD simulations in complex terrain often struggle to reproduce the detailed vertical structure of wind profiles at a given moment in time, even though they may perform reasonably well in a long-term, averaged sense. This limitation is explicitly acknowledged and is, in fact, one of the motivations for the proposed approach. In the present methodology, CFD simulations are not used as direct profile-to-profile references. Instead, they are employed to mitigate temporal inhomogeneity between lidar observations by providing a dynamically consistent flow field from which robust, physically meaningful parameters can be derived. These eight parameters detailed in the methodology are specifically chosen because they are less sensitive to instantaneous mismatches and more representative of the flow characteristics that can be reliably captured by CFD at a given snapshot in time. Since these eight parameters are discussed in comment #1, #2 and #3 in a similar manner, we will discuss them in detail once here:

1. GHI – this is an obvious proxy for radiative forcing and cloud cover. GHI varies smoothly in space and time and is largely insensitive to small-scale turbulence or local flow distortions. The HICAR model is based on COSMO-1 (1km resolution, 81 vertical layers) weather model, which is generally reasonably good at estimating this value even in the complex terrain.
2. Atmos. Stabil. Is based on the gradient of the levels from 10 to 247m, and is therefore a bulk thermal stratification of the lower atmosphere. Since it is based on temperature, humidity and pressure that vary smoothly over local terrain at these elevations, it is reasonable to take a single horizontal grid column to base this information from and use it for the local couple hundred meters of the pass top. Additionally, CFD models are generally more reliable at reproducing the bulk stability than the fine-scale velocity fluctuations, making it more robust than a CFD wind

profile.

3. Vertical shear magnitude, this is derived form the horizontal wind vectors over a 2km transect which covers tens of grid cells and averages the bulk shear from 10 to 247m. This averaging reduces sensitivity to local topographic effects. Rather than attempting to match the exact shape of the wind profile, this parameters characterises the overall momentum redistribution with height. This flow property is most consistent than a mere single column CFD cell.
4. Variance of the vert. turb., again we average over a 2km transect as well as the 10 to 247 m heights. This metric suppresses any sensitivities to individual turbulent eddies or short-lived local events. While CFD may not accurately reproduce instantaneous turbulence structure as the reviewer suggests, it can capture the relative differences in TI associated with the stability, shear, and terrain-induced forcing.
5. And,
6. Synop. Wind components are derived from level 20 of HICAR at approx. 5km elevation and represents the large-scale forcing of the lfow. At this altitude, the wind is largely decoupled from local terrain effects and surface-layer turbulence. These are essentially direct values taken from COSMO-1, which is generally considered to be accurate at this elevation.
7. And,
8. Transect-averaged wind components are derived from levels 3-5 (61-136m) are used as a proxy for the bulk flow in the rotor relevant layer. Spatial averaging over the 2km transect again helps reduce the influence of localised flow acceleration ,separation, or recirculation induced by the individual complex terrain effects. Thus reflecting the dominant flow orientation and strength experienced by the wind turbines rather than point-scale variability.

Overall, these eight parameters are concretely averaged, Gotthard-wind-park-scale single value parameters that serve as a physically interpretable meteorological overview that is significantly more robust than CFD wind profiles. The revised manuscript now explicitly explains the rationale behind this selection in the methodology section, emphasizing that these parameters are better suited for comparative analysis than full profile matching. For example in the third version of the manuscript (which was already submitted, but not available for you during review), the title has been adapted to better reflect this new method, an additional paragraph to introduce these CFD parameters better, and the conclusion has improved to reflect on the importance of the CFD parameters in the methodology. The introduction now better reflects the scope, limitations, and intended applicability of the method in a version that was already resubmitted before your review was submitted. These revisions were specifically aimed at clarifying that the approach is designed for profile matching and flow characterization, rather than as a standalone wind resource assessment tool requiring pre-existing turbines. We hope this clarification resolves the reviewer's concern and better highlights the intended role of CFD simulations within the proposed framework. Concretely, we have improved the rationale for the CFD simulations in the methodology to make the transition from wind turbine data to CFD data more obvious and logical:

"HICAR characteristic features Building on the nacelle-based matching, we refine the inter-comparison by introducing eight characteristic parameters derived from the HICAR v1.1 mesoscale model. The model provides wind fields on a 50 m horizontal grid with 32 vertical

levels, which were interpolated to the nacelle positions (98 m a.g.l.), and to the ten LiDAR locations with their respective range gates. In the complex terrain, instantaneous wind profiles are strongly influenced by transient turbulence and local flow distortions, which limits the applicability of direct profiles matching. Numerical model output is therefore only used here to provide a dynamically consistent description of the ambient meteorological conditions at the time of observation that are valid for the Gotthard wind park domain. HICAR is not employed to reproduce individual wind profiles, but to derive a small set of averaged, physically meaningful parameters that are less sensitive to local, and short-lived variability that is common in this terrain, and rather difficult to simulate accurately with wind models. Alongside the five local wind turbine nacelle wind measurements, we define eight parameters that characterise the inflow conditions from the Gotthard wind park domain, which is chosen to be around Turbine 4 as it is the most central turbine:"

1. The accuracy of ground-based wind lidar profilers in measuring mean wind speed depends on the assumption of spatial flow homogeneity. In the revised manuscript, CFD data are used to support the hypothesis that the flow distortion at the locations where the wind lidar profiler was installed, is minimal. However, this conclusion depends on the reliability of the CFD simulation. Furthermore, even if this assumption holds for the specific site studied, flows in complex terrain are inherently inhomogeneous. Inhomogeneities that are even stronger when the lidar's measurement volume includes turbine wakes (as the case for example of the L9 profile in Figure 11). This will introduce a bias in estimating the mean wind vector and would have an even greater impact on the accuracy of second-order moments derived from lidar measurements.

We thank the reviewer for this detailed comment and agree that ground-based wind lidar profilers inherently rely on assumptions of spatial flow homogeneity within the measurement volume. This limitation is well known and applies to essentially all remote-sensing–based wind measurements in complex terrain. In the revised manuscript, CFD simulations are not used to claim absolute accuracy of the LiDAR-derived wind statistics, nor are they used to validate the lidar measurements directly. Instead, CFD is employed in a supporting role, using a selection of eight robust flow parameters that are less sensitive to local, instantaneous flow distortions. Importantly, CFD wind profiles themselves are never used directly in the matching algorithm. This distinction is critical and is now clarified more explicitly in the methodology. (details on the eight parameters in the previous comment response) Regarding flow distortion at the lidar locations, we fully agree that any conclusion drawn from CFD is conditional on the reliability of the simulation. For this reason, we deliberately avoid relying on point-wise CFD wind speeds and instead focus on bulk flow characteristics that are known to be more robust in complex terrain. The CFD results are therefore used to exclude strong, systematic flow distortion, not to assert perfect flow homogeneity. The reviewer is also correct that flows in complex terrain are inherently inhomogeneous and that this inhomogeneity is exacerbated when the LiDAR measurement volume intersects turbine wakes (e.g., the L9 profile in Figure 11). This will inevitably introduce biases in the estimated mean wind vector and, even more so, in second-order moments such as turbulence intensity. However, this limitation is not specific to the present study, but rather reflects the current state of the art in wind energy field measurements. Volume averaging and 10-minute statistics are standard practice in both research and industry, particularly in terrain where erecting multiple 100+ m meteorological towers is not feasible. With respect to second-order moments, we emphasize that the

turbulence quantities used in this study are 10-minute averaged values, consistent with standard wind energy assessment methodologies. While these cannot capture the full complexity of turbulence that would be measured by dense arrays of sonic anemometers, such measurements are practically impossible at multiple sites across a mountain pass. The presented approach therefore represents the best achievable compromise between spatial coverage and measurement fidelity under realistic field conditions. Finally, we note that a follow-up study by the authors (currently available as a preprint here: https://wes.copernicus.org/preprints/wes-2025-271/) uses the lidar-derived 10-minute mean wind speed and turbulence intensity obtained with the present methodology to predict 10-minute cumulative wind turbine power output, showing remarkably good agreement with observations. This independent result provides strong evidence that, despite the acknowledged limitations, the derived wind statistics are physically meaningful and representative of the flow relevant for wind energy applications. We have added further clarification in the revised manuscript to explicitly acknowledge these limitations and to better position the method within the context of current best practices in complex-terrain wind measurements: In the results section, Turbulence Kinetic Energy:
"We preface this subsection by noting that turbulence quantities derived from Doppler wind LiDAR measurements are inherently influenced by volume averaging along the laser beam and over the sampling volume, which particularly affects second-order moments such as variance and, consequently, turbulence kinetic energy. As a result, the absolute magnitude of TKE should not be interpreted as a point-scale turbulence intensity in the classical sense, but rather as a relative measure for comparing different flow regimes along the transect. Despite this limitation, scanning LiDAR remains the state of the art for capturing spatial variability in turbulence over complex terrain, as the deployment of tall meteorological masts at comparable heights and at multiple locations along a 2 km transect is not practically feasible." And in the Conclusions section: *"…. A qualitative assessment of the compound effects of complex terrain on the incident wind agrees well with the turbine data. The applicability of the presented approach may be reduced at exposed hilltop or ridge locations, where strong flow inclination and separation can violate the homogeneity assumptions required for ground-based Doppler LiDAR measurements. This interpretation should be understood in a relative sense, as turbulence metrics derived from Doppler LiDAR are affected by volume averaging and therefore describe spatially coherent variability rather than point-scale turbulence intensity."*

1. The authors state that their intent is not to present a climatological analysis but to investigate spatial flow variability. However, it is unclear how spatial variability can be decoupled from temporal variability. While CFD simulations could provide insight, this would require validation demonstrating the model's accuracy in predicting wind profiles for the complex terrain under study.

The intent of this study is not to achieve a strict mathematical separation of spatial and temporal variability, but rather to reduce the influence of temporal variability sufficiently to allow a meaningful investigation of relative spatial flow variability across measurement locations. This distinction is important. In practice, temporal variability is mitigated through a combination of: (i) simultaneous multi-profile lidar measurements, (ii) the use of time-averaged (10-minute) statistics consistent with standard wind energy practice, and (iii) the use of CFD-derived flow descriptors that are robust to instantaneous fluctuations and do not rely on exact profile matching. (as explained in the response to comment #1) As emphasized throughout the revised manuscript, CFD simulations are not used to reproduce instantaneous wind profiles and are therefore not required to accurately predict profile

shapes at a given moment in time. Instead, CFD provides a dynamically consistent reference flow that helps identify large-scale spatial patterns and supports the interpretation of observed variability. The parameters extracted from the CFD simulations are chosen specifically because they are less sensitive to short-term temporal variability and known limitations of CFD in complex terrain. We fully agree that CFD-based prediction of exact wind profiles in complex terrain would require extensive validation, which is beyond the scope of this work. However, such validation is not a prerequisite for the present analysis, as the CFD simulations are not used in a prognostic or climatological sense, nor as a direct reference for the lidar measurements. In line with comment the two comments above, we have further clarified this point in the revised manuscript by explicitly stating that the analysis aims to minimize, rather than eliminate, temporal variability in order to examine spatial flow variability under realistic field conditions. "...."

1. In the section "Gotthard sequential LIDAR transect experiment", it is stated that HICAR "can resolve terrain-induced flow features at the hectometer scale." Later, in "Instrumentation overview", the resolution is given as 50 m for the HICAR v1.1 model. Regardless of which value is correct, I am concerned whether this spatial resolution is sufficient to estimate the expected bias in mean wind speed caused by spatial inhomogeneities.

The term "hectometer-scale" refers to the target application scale of the HICAR model and does not imply a fixed grid spacing of 100 m. In the present study, the HICAR v1.1 simulations are performed at a horizontal resolution of 50 m, as stated in the "Instrumentation overview" section. This resolution lies within the hectometer scale and is consistent with the design of the HICAR model. Regarding the reviewer's concern about whether this spatial resolution is sufficient to estimate potential biases in mean wind speed due to spatial inhomogeneities, we note that this question has been explicitly addressed in previous studies. In particular, the two references already cited in the manuscript demonstrate that resolutions on the order of 50–100 m are adequate to capture terrain-induced flow features relevant for assessing lidar volume-averaging effects and associated biases in complex terrain: https://doi.org/10.5194/gmd-16-5049-2023, https://doi.org/10.3389/feart.2024.1388416 We have revised the text to more clearly state that a 50 m horizontal resolution is used throughout this study, and to avoid any potential misunderstanding arising from the terminology.

1. In the section "LIDAR details", the manuscript mentions "five pulsed laser beams, which are magnetically controlled by the instrument." Could the authors clarify what is meant by "magnetically controlled"? Additionally, the text states that the "return signal... 30 mW mean power laser is recaptured." Is this accurate?

The above-mentioned excerpts are direct mentions of the WindCube's manual that accompanied the instrument that was delivered by VAISALA. Therefore, we assume that the 30 mW mean laser power is accurate, and that the laser beams are magnetically controlled. The manual does not state exactly how this magnetic controller works exactly, but after some research on this topic this likely has to do with how a strong magnetic field can influence the reflection conditions of the prism such that the beam is reflected in one of the 5 directions; vertical, or in one of the four cardinal directions.
Since this information is not essential for the understanding of wind energy in the complex terrain, we elect to not elaborate this any further in the manuscript, however we will include a citation to the exact manual this information this was taken form.

Competing Interests: No competing interests were disclosed.

Reviewer Report 06 January 2026

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?

Shengming Tang
Shanghai Typhoon Institute of China Meteorological Administration, Shanghai, China

Thank you for your thoughtful revision. Regarding my second point concerning the vertical variation of wind direction at L8, I wish to clarify that my focus was specifically on wind direction changes with height (vertical profile), not on lateral deflection over a horizontal distance. The common expectation of wind veering with height in the Northern Hemisphere stems from the Ekman spiral in the planetary boundary layer—a theory fundamentally driven by the Coriolis force balancing friction over hundreds of meters vertically. Therefore, the observed wind rotation at L8 is primarily driven by local topography, which overwhelms and distorts the expected background veering pattern. I suggest the manuscript could briefly acknowledge the classical Ekman/Coriolis framework as the baseline atmospheric expectation that is being locally disrupted. This would provide a more complete and pedagogically sound explanation for readers.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Boundary layer meteorology

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 16 Jan 2026

Brandon van Schaik

Shengming Tang
Thank you for your thoughtful revision. Regarding my second point concerning the vertical variation of wind direction at L8, I wish to clarify that my focus was specifically on wind direction changes with height (vertical profile), not on lateral deflection over a horizontal distance. The common expectation of wind veering with height in the Northern Hemisphere stems from the Ekman spiral in the planetary boundary layer—a theory fundamentally driven by the Coriolis force balancing friction over hundreds of meters vertically. Therefore, the observed wind rotation at L8 is primarily driven by local topography, which overwhelms

and distorts the expected background veering pattern. I suggest the manuscript could briefly acknowledge the classical Ekman/Coriolis framework as the baseline atmospheric expectation that is being locally disrupted. This would provide a more complete and pedagogically sound explanation for readers.
Response: We thank the reviewer for clarifying their comment. We agree that acknowledging the referred framework is beneficial. We believe, the best location for this would be the Results section: "Windshear and veer". We address this in the manuscript by adding the following paragraph in this subsection: *"Under idealized conditions in the planetary boundary layer, wind direction is expected to veer with height in the Northern Hemisphere as a result of the Ekman balance between surface friction and the Coriolis force. This Ekman-induced veering typically develops gradually over several hundred meters in the vertical. At L8, however, the observed wind direction changes with height strongly deviate from this classical framework and are instead dominated by local topographic forcing, which overwhelms and distorts the background Ekman veering."*

Competing Interests: No competing interests were disclosed.

Reviewer Report 30 December 2025

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?

Feng Guo
Shanghai Jiao Tong University, Dongchuan Road, Shanghai, China

The manuscript entitled *"Resolving three-dimensional wind velocity fields with sequential wind Doppler LiDAR for wind energy in complex terrain – Gotthard Pass, Switzerland"* aims to characterize the wind conditions over the complex terrain of the Gotthard Pass in Switzerland. The study provides valuable insights into the wind characteristics driven by topographically channelled flow in this region, thereby supporting future decisions in wind farm design under similar conditions. The work demonstrates strong engineering merit; however, several improvements are recommended.

1. The manuscript title does not clearly reflect the methods applied in the study. The proposed approach requires CFD simulations in combination with nacelle anemometer measurements. However, the title gives the impression that wind lidar alone is sufficient to obtain the three-dimensional wind velocity distributions, which is not accurate.

2. Although the current study is conducted in complex terrain, the five turbines are aligned along a channel where the wind behavior is considerably less complicated than at hilltop locations. In hilly areas, flow inclination and flow separation can violate the homogeneous flow assumption required for ground-based lidar measurements. This limitation should be clearly acknowledged and emphasized by the authors.

3. The quality of the figures—especially Figure 14—needs to be improved. Clearer visualization and higher resolution are recommended.

4. Some grammatical and language issues are observed. For example, “a complete profile over the swept area by the turbine blade” should be “a complete profile over the swept area by the turbine blades,” and “a blade diameter of 92 m” should be “a rotor diameter of 92 m.” The authors are encouraged to carefully proofread the manuscript to correct similar issues.

5. LiDAR horizontal flow homogeneity assumption:
The authors are encouraged to illustrate the horizontal flow homogeneity assumption by presenting the simulated mean flow field in a figure.

6. “During snow-covered periods, which are not included in our LiDAR measurement period.”
Blade icing, which reduces aerodynamic efficiency, may also contribute to performance variations and should be acknowledged by the authors.

7. “Conclusion.”
The authors should refine the conclusion. Based on the results presented, the sequential LiDAR measurement technique appears to be a strong candidate for improving wind profile characterization in channelized wind sites within complex terrain.

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Wind resource assessment, wind lidar, wind turbine aero-elastic

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 16 Jan 2026

Brandon van Schaik

Feng Guo
The manuscript entitled “Resolving three-dimensional wind velocity fields with sequential wind Doppler LiDAR for wind energy in complex terrain – Gotthard Pass, Switzerland” aims to characterize the wind conditions over the complex terrain of the Gotthard Pass in Switzerland. The study provides valuable insights into the wind characteristics driven by topographically channelled flow in this region, thereby supporting future decisions in wind farm design under similar conditions. The work demonstrates strong engineering merit; however, several improvements are recommended.
1. The manuscript title does not clearly reflect the methods applied in the study. The proposed approach requires CFD simulations in combination with nacelle anemometer measurements. However, the title gives the impression that wind lidar alone is sufficient to obtain the three-dimensional wind velocity distributions, which is not accurate.
Response: We thank the reviewer for catching this shift in methodology had not caught up to our manuscript title. We have changed the title from: *“Resolving three-dimensional wind velocity fields with sequential wind-Doppler LiDAR for wind energy in the complex terrain - Gotthard Pass, Switzerland”* To: *“Resolving three-dimensional wind velocity fields in complex terrain using sequential wind-Doppler LiDAR, CFD, and wind turbine measurements – Gotthard Pass, Switzerland”*

2. Although the current study is conducted in complex terrain, the five turbines are aligned along a channel where the wind behavior is considerably less complicated than at hilltop locations. In hilly areas, flow inclination and flow separation can violate the homogeneous flow assumption required for ground-based lidar measurements. This limitation should be clearly acknowledged and emphasized by the authors.

Response: We agree with the reviewer and have explicitly acknowledged this limitation in the Sequential LiDAR transect subsection. The revised text now states that the turbines are aligned along a channelled plateau with less complex flow than exposed hilltop locations, and that flow inclination and separation in more complex terrain can violate the homogeneity assumption required for ground-based Doppler LiDAR measurements. This is now in addressed in the “Sequential LiDAR transect” subsection in the Field site, instrumentation and modelling Section:
“… It is noted that, despite the overall complex terrain of the Gotthard Pass, the turbines and LiDAR transect are aligned along a topographically channeled plateau. As a consequence, the flow conditions encountered here are less complex than at exposed hilltop or ridge locations, where flow inclination and flow separation may violate the horizontal homogeneity assumption required for ground-based Doppler LiDAR wind retrievals. This represents a limitation of the present study.”

3. The quality of the figures—especially Figure 14—needs to be improved. Clearer visualization and higher resolution are recommended.

Response: We believe this is an issue with the typesetting of composite figures as the quality of the figures in our submission folder are much better. We will address this by pre-

typesetting the composite figures (especially 14 and 15) and delivering a single high-DPI figure.

4. Some grammatical and language issues are observed. For example, “a complete profile over the swept area by the turbine blade” should be “a complete profile over the swept area by the turbine blades,” and “a blade diameter of 92 m” should be “a rotor diameter of 92 m.” The authors are encouraged to carefully proofread the manuscript to correct similar issues.

Response: We apologize for these issues; we have proof read the manuscript to address such issues as well as the ones mentioned here.

5. LiDAR horizontal flow homogeneity assumption: The authors are encouraged to illustrate the horizontal flow homogeneity assumption by presenting the simulated mean flow field in a figure.
Response: We thank the reviewer for this suggestion and agree that illustrating the horizontal homogeneity assumption would be valuable if meaningful spatial variability could be resolved. We examined the simulated mean flow fields from the HiCAR v1.1 model. However, at its 50 m horizontal resolution, the model does not resolve sub-grid-scale variability over the 60-140m spacing of the individual LiDAR beams that are relevant for the swept are of the turbine blades with the 28° angle from the horizontal. Showing the simulated mean flow does not help to address this as it appears nearly homogeneous across the transect, and a figure would not provide additional insight into the validity of the LiDAR homogeneity assumption and could potentially be misleading.
Instead, we have clarified this limitation in the manuscript by explicitly stating that the homogeneity assumption cannot be directly illustrated using the available model resolution and must be interpreted as a methodological assumption rather than a resolved flow feature in the subsection “LiDAR horizontal flow homogeneity assumption”:
“… Additionally, at the horizontal scales relevant for the LiDAR measurements, the HiCAR v1.1 model resolution (50 m) does not resolve sub-grid flow variability within the LiDAR sampling volume. Consequently, model-derived mean flow fields appear horizontally smooth over the transect length and are therefore not well suited to visually illustrate the LiDAR horizontal homogeneity assumption.”

6. “During snow-covered periods, which are not included in our LiDAR measurement period.” Blade icing, which reduces aerodynamic efficiency, may also contribute to performance variations and should be acknowledged by the authors.
Response: We have acknowledged these points now as follows:
“During snow-covered periods, which are not included in our LiDAR measurement period, but are partly represented in the longer time domain of Figure 15b, a general decrease in efficiency is observed over all the turbines. In addition to surface-related and atmospheric effects, blade icing during snow-covered periods may further reduce aerodynamic efficiency and contribute to the observed performance decrease. While icing is not explicitly quantified in this study, it is a known factor affecting turbine performance in high-alpine winter conditions. …”

7. “Conclusion.” The authors should refine the conclusion. Based on the results presented, the sequential LiDAR measurement technique appears to be a strong candidate for improving wind profile characterization in channelized wind sites within complex terrain.

Response: We thank the reviewer for this constructive suggestion and agree that the applicability of the presented method should be more clearly defined. The Conclusion has been refined accordingly to better reflect the scope of the results.
For example, we now state in the opening sentence that the method applies to *"channelized flow conditions within complex terrain"* rather than complex terrain in general. Furthermore, the concluding paragraph has been revised to emphasise that the sequential LiDAR technique is *"an excellent candidate to improve wind profile characterization in channelized wind sites within complex terrain, where flow alignment and limited separation support the underlying LiDAR measurement assumptions."* As has been suggested by other comments above. We now also explicitly acknowledge a key limitation by noting that *"the applicability of the presented approach may be reduced at exposed hilltop or ridge locations, where strong flow inclination and separation can violate the homogeneity assumptions required for ground-based Doppler LiDAR measurements."*

Competing Interests: No competing interests were disclosed.

Version 1

Reviewer Report 22 February 2025

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Nikolas Angelou
Technical University of Dermark (DTU), Frederiksborgvej, Denmark

The manuscript entitled:" Resolving three-dimensional wind velocity fields with sequential wind-Doppler LiDAR for wind energy in the complex terrain – Gotthard Pass, Switzerland" presents a study of the wind conditions over a complex terrain. The topic is relevant in a wind energy context, since as it is also pointed by the authors, the wind resource assessment over complex terrain is a challenging task that requires wind observations. For this purpose, the authors performed a field study using a ground-based wind lidar profiler, which was sequentially moved to different locations, and developed a methodology to characterise the spatial variability of the wind conditions. Even though the topic is interesting the proposed methodology has the following weaknesses:

1. The wind lidar data set consists of observations acquired in different locations during a 3-month period. During such a period the wind conditions change, therefore it is not straightforward to inter-compare the wind profile acquired over one week in June in one location with the one measured in September in another location. Additionally, the measurement duration at each location varies from 1 to 12 days. This duration is quite limited and further as the authors state the measurements were acquired over different

times of the day. Therefore, the measured wind profiles are not necessary characteristic of the wind conditions at the measured locations.

2. The matching algorithm proposed, which is one of the innovations of this study, is based on grouping the acquired wind lidar data set according to the hub-height wind speed measured by the nacelle-based anemometers. However, similar wind conditions at the hub-height do not necessary correspond to a specific wind profile. Furthermore, the application of this method requires the measurement of the wind conditions over different locations at the hub height of a wind turbine. Therefore, it cannot be used in the context of a wind resource assessment.
3. There is no discussion in the manuscript about the flow distortion of the nacelle-mounted anemometer and the reliability of the measurement of the longitudinal and transverse component of the horizontal wind vector.
4. The accurate measurement of the wind profile using a ground-based wind profile assumes of horizontal flow homogeneity. An assumption that is not valid over a complex terrain and thus the derivation of the mean wind profile using a ground-based wind lidar profiler is not necessarily correct. This is even more relevant, when wind lidar profiler data are used to estimate the standard deviation of the wind vector components.
5. Based on the locations where the wind lidar measurements were acquired and the examined wind direction sectors, I imagine that at least part of the wind lidar measurements are biased by the wake generated by the wind turbines.

Based on the above points, I think that the statistical analysis performed is not appropriate and cannot support the conclusions drawn. Furthermore, the quality of the figures and the use of certain references should be improved/corrected (for example the reference [10] is not presenting a validation of a CFD simulation). Therefore, I unfortunately think that the article cannot be considered for indexing in its current version.

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
No

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
No

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
No

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Wind Lidar, Wind Energy, Atmospheric Boundary Layer

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

Author Response 11 Nov 2025

Brandon van Schaik

Nikolas Angelou

1. The wind lidar data set consists of observations acquired in different locations during a 3-month period. During such a period the wind conditions change, therefore it is not straightforward to inter-compare the wind profile acquired over one week in June in one location with the one measured in September in another location. Additionally, the measurement duration at each location varies from 1 to 12 days. This duration is quite limited and further as the authors state the measurements were acquired over different times of the day. Therefore, the measured wind profiles are not necessary characteristic of the wind conditions at the measured locations.

We acknowledge that the LiDAR measurements at each site are not necessarily representative of the full seasonal wind variability, nor are they sufficient to define a robust statistical wind distribution or wind rose for each location. However, the intent of this study is not to present a climatological analysis, but rather to investigate spatial variability and flow characteristics during the measurement period. In response to this comment, and those made by another reviewer, we have complemented the LiDAR observations with additional CFD simulations covering the full 3-month campaign period and the entire mountain pass. These simulations provide spatially and temporally continuous wind fields that support the short-term measurements. Specifically, we have identified 8 characteristic features including, global horizontal irradiance, atmospheric stability, vertical shear magnitude, variance of the vertical turbulence, an average of the transect wind field, and the synoptic wind at 5km. To this end, the Methodology section is completely overhauled and Results updated accordingly. We believe this addresses the reviewer's concern by providing a more complete picture of the wind conditions across all sites.

1. The matching algorithm proposed, which is one of the innovations of this study, is based on grouping the acquired wind lidar data set according to the hub-height wind speed measured by the nacelle-based anemometers. However, similar wind conditions at the hub-height do not necessary correspond to a specific wind profile. Furthermore, the application of this method requires the measurement of the wind conditions over different locations at the hub height of a wind turbine. Therefore, it cannot be used in the context of a wind resource assessment.

Thanks to your suggestions we have opted to provide additional CFD simulations to help contextualize the turbine wind vector matching algorithm. We have updated the matching algorithm as elaborated in the previous comments. We refer to the Methodology section of the manuscript for the detailed overview of the 8 characteristic features that are now implemented.

1. There is no discussion in the manuscript about the flow distortion of the nacelle-mounted anemometer and the reliability of the measurement of the longitudinal and transverse component of the horizontal wind vector.

Nacelle distortion is an important part when considering nacelle measured wind speed to

wind power generated by the wind turbine. In this study we only ever consider nacelle measured wind speeds relative to measurements from the same anemometer in the same location of the same turbine. Therefore, this distortion in not relevant as the same bias is included in all comparisons and cancels out. With the new introduction of CFD simulations, this issue becomes valid in a hypothetical case where we compare CFD simulations to the nacelle measurement. We address in the manuscript that this distortion is present, and that it is not possible to directly compare them in this case. **Addressed in the manuscript as such:** *"We are unable to compare the HICAR wind vectors at the wind turbine nacelles with the in-situ data measured by the anemometers due to the flow distortion of the nacelle which is not simulated."*

1. The accurate measurement of the wind profile using a ground-based wind profile assumes of horizontal flow homogeneity. An assumption that is not valid over a complex terrain and thus the derivation of the mean wind profile using a ground-based wind lidar profiler is not necessarily correct. This is even more relevant, when wind lidar profiler data are used to estimate the standard deviation of the wind vector components.

With the WindCube V2.1 profiler, the angled lasers are pointed 28° from the vertical. This roughly means that at 100m the N and S beam are ~100m apart. With our newly available CFD simulations we can now explore how much the wind vector has changed at 100m and 300m height with 100m and 300m horizontal spacing respectively in all 4 cardinal directions. Vertical inhomogeneity in both the N-S and E-W direction at corresponding the corresponding height above the LiDAR show the following biases and standard deviations:
100m above LiDAR
(100m horizontal spacing) Bias [m/s] Standard deviation [m/s] N – S differences in v (dir. north) 0.094 0.116 E – W differences in u (dir. east) 0.002 0.251 N – S & E – W differences in w (dir. up) 0.012 0.058 **300m above LiDAR**
(300m horizontal spacing) Bias [m/s] Standard deviation [m/s] N – S differences in v (dir. north) 0.019 0.392 E – W differences in u (dir. east) -0.085 0.229 N – S & E – W differences in w (dir. up) 0.048 0.230 Biases are all <0.1 m/s and therefore neglectable compared to the error of the LiDAR. Standard deviations are higher and can be explained as follows. In the N-S direction, which is the prevailing direction, you can expect larger changes as you increase horizontal spacing as there is a strong channeling effect. Yet, still errors are within < 0.5m/s which is less than the LiDAR standard measuring error. For E-W direction, the error at lower height is slightly bigger which is likely due to surface effects. Our CFD simulations don't include thermal winds such as katabatic and anabatic winds due to thermal forcing, therefore errors may be a bit bigger in reality. But still far within reason to assume homogeneity. Finally, there is a small vertical wind speed error as the pass winds have to go up over the pass and then down again. However, with the angle of the laser at 28° from the vertical, the effective error is halved (sin(28°)~=0.5) and therefore also well within reason. As the manuscript contains already a lot of tables and information, we have opted to not show this table in the manuscript and rather address this issue in the following subsection:
Addressed in the manuscript as such: *"LiDAR horizontal flow homogeneity assumption In complex terrain, concerns may arise regarding the applicability of Doppler wind LiDARs, as horizontal flow inhomogeneities can violate the homogeneity assumption underlying the retrieval of vertical wind profiles. The WindCube V2.1 profiler employs four beams inclined 28° from the vertical, corresponding to a horizontal separation of approximately 100 m between opposing beams at 100 m height. To evaluate potential impacts of horizontal inhomogeneity, we analysed*

CFD simulations across representative distances of 100 m (at 100 m height) and 300 m (at 300 m height) in all four cardinal directions. This shows that the mean biases in all wind components remain below 0.1 ms^(-1), which is negligible relative to the intrinsic measurement uncertainty of the LiDAR. Standard deviations are generally below 0.5 ms^(-1), with slightly larger values in the north–south direction, attributable to valley channeling, and in the east–west direction near the surface, likely related to surface effects. Although the CFD simulations do not represent thermally driven flows such as katabatic or anabatic winds, which may increase variability in reality, the observed deviations are on the order of the intrinsic error of the LiDAR, thus supporting the validity of the horizontal homogeneity assumption. Consequently, LiDAR-derived vertical profiles can be interpreted without additional corrections."

1. Based on the locations where the wind lidar measurements were acquired and the examined wind direction sectors, I imagine that at least part of the wind lidar measurements are biased by the wake generated by the wind turbines.

Indeed we do observe some wind profiles in the LiDAR data, particularly for Northerly winds incident on Turbine 2 going to LiDAR 9, that would fit wake distortion. However, this is not a problem to our methods, but rather a feature of the sequential LiDAR transect. We do not use the LiDAR data to create matches, rather we use the matches to show off LiDAR profiles to visualize the transect 3D wind profile. Since wake distortion is an inherent part of the 3D wind field captured along the transect, its presence helps illustrate the spatial extent of the wake, specifically where it emerges and where it dissipates. The CFD simulations in HICAR do not include the wind turbines and thus also do not suffer from this during the matching algorithm.

1. Furthermore, the quality of the figures and the use of certain references should be improved/corrected (for example the reference [10] is not presenting a validation of a CFD simulation). Therefore, I unfortunately think that the article cannot be considered for indexing in its current version.

We have addressed figure quality and said reference.

Competing Interests: No competing interests were disclosed.

Reviewer Report 12 February 2025

https://doi.org/10.21956/openreseurope.20665.r49933

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?

Shengming Tang
Shanghai Typhoon Institute of China Meteorological Administration, Shanghai, China

In this study, a deployment method called sequential wind-Doppler LiDAR deployment is introduced. This method proposes a matching algorithm that can group wind profiles among different LiDARs. The proposed deployment method is novel and practical because only a single wind-Doppler LiDAR is needed to construct the three-dimensional wind field instead of multiple

synchronized LiDARs. This is an important work for the observational study of the near-surface wind field and the design and operation of wind power generation in mountainous areas. The structure is well designed, the method is innovative, and the analysis is detailed, comprehensive and thorough, with its conclusions are adequately supported by the results. Although this work has good academic and engineering merits, some issues are still needed to be addressed before publication.

1. Table 1: Please explain clearly how to understand the values of Easting (m) and Northing (m)? If a map projection is used, please explain it in the main text.

2. As shown in Figure 11, for northerly wind, the wind direction of L4 rotates clockwise with the increase of height. However, the wind direction of L8 rotates anticlockwise with the increasing height, which is not consistent with the common sense that the wind direction rotates clockwise with the increasing height in the northern hemisphere. Please explain why.

3. Page 16: Turbulence kinetic energy (TKE) *k* exhibits bi-modal distributions. What is the meaning of 'bi-modal'?

4. Page 16, Equation 8: The authors assume that the mean wind speed is symmetrical until the second order (e.g. normal distribution). Actually, it is easy to verify whether the wind speed is normally distributed when having the raw data. Please provide the relevant verification process and statistical results.

5. Figures 7, 9, 10, 11 are blurry, please increase the figure resolution.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Boundary layer meteorology

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 11 Nov 2025

Brandon van Schaik

Shengming Tang

1. Table 1: Please explain clearly how to understand the values of Easting (m) and Northing (m)? If a map projection is used, please explain it in the main text.

Addressed in the manuscript as such: "Table 1. Instrumentation and data availability. Easting and Northing coordinates in the Swiss Coordinate system LV95 (EPSG:2056)."

1. As shown in Figure 11, for northerly wind, the wind direction of L4 rotates clockwise with the increase of height. However, the wind direction of L8 rotates anticlockwise with the increasing height, which is not consistent with the common sense that the wind direction rotates clockwise with the increasing height in the northern hemisphere. Please explain why.

Coriolis forces don't act on this scale (~1km). The forces of the topography greatly outweigh any other apparent rotational forces. The Coriolis acceleration is defined as: $\boldsymbol{a}=-2\boldsymbol{\omega}\times\boldsymbol{v}$, $\boldsymbol{a}\leq 2\boldsymbol{\omega}\boldsymbol{v}$ $\vec{a}=-2(\vec{\omega}\times\vec{v}),|\vec{a}|\leq 2|\vec{\omega}||\vec{v}|$ Where the second equation holds as the rotational vector omega and velocity vector are always perpendicular or very close to perpendicular. With omega pointing to the geometric south pole, and in the maximum acceleration case, the wind pointing true east or true west, we find the maximum possible acceleration in a clockwise direction. Earth rotates at $\boldsymbol{\omega}=2\pi$ rad/day$24h day\ 60min h 60sec min=7.27\cdot 10\text{-}5 rad/s$ $|\vec{\omega}|=\frac{2\pi\ \mathrm{rad/day}}{24\frac{h}{day}60\frac{min}{h}60\frac{sec}{min}}=7.27\cdot 10^{-5}rad/s$. For the maximum wind speed of $\boldsymbol{v}$=25ms $|\vec{v}|=25\frac{\mathrm{m}}{s}$, then $\boldsymbol{a}max=3.64\cdot 10\text{-}3 m/s2$ $|\vec{a}|_{max}=3.64\cdot 10^{-3}m/s^2$, which over the longest distance we have measured over the pass of approximately 1500m, would result in $1.5\ km25\ ms\cdot 3.64\cdot 10\text{-}3 ms2=0.28\ m/s,$ $\frac{1.5\ km}{25\frac{m}{s}}\cdot 3.64\cdot\frac{10^{-3}m}{s^2}=0.28\ m/s,$ of perpendicular wind speed deviation. Which equates to a rotation of $8.73\ mrad=0.50°$ $8.73\ mrad=0.50°$. In fact, this rotation is independent of wind speed v, thus under no wind speeds could this deviation be greater than 0.50°. We can conclude from this that the Coriolis force is of negligible influence, and the topographic channelling forces are of much greater effect. **Addressed in the manuscript as such:** "This veering effect can not be explained by any other apparent forces on the wind such as the Coriolis force which actually act in the opposite direction. In fact, the maximum veering that can be introduced by the Coriolis effect over the Gotthard upper plateau, approximately 1500m in length, is 0.50°, independent of wind speed. This is far below the veering observed by the channelling effect created by the topography."

1. Page 16: Turbulence kinetic energy (TKE) *k* exhibits bi-modal distributions. What is the meaning of 'bi-modal'?

A bi-modal distribution is a probability distribution with two modes. We can separate these two distributions, with different modes, by considering northerly and southerly winds

separately as they exhibit very different characteristics when considering the turbulence kinetic energy statistics. **Addressed in the manuscript as such:** "Turbulence kinetic energy (TKE) k (Equation 6), equation 5) exhibits bi-modal distributions where northerly and southerly winds exhibit very different TKE characteristics,. This bi-model distribution is similar to the wind speed, along the LiDAR transect as shown in Figure 14"

1. Page 16, Equation 8: The authors assume that the mean wind speed is symmetrical until the second order (e.g. normal distribution). Actually, it is easy to verify whether the wind speed is normally distributed when having the raw data. Please provide the relevant verification process and statistical results.

Thank you for this very interesting suggestion. We actually refer to the *wind deviations from the mean* being normally distribution (symmetrical until the second order), but we assume that we refer to the same principle here. We verified with our 1-second resolution wind data measured by the LiDAR throughout the campaign. We observe that these deviations from the mean are actually not perfectly normally distributed, but is still symmetrical to second order. There exist other symmetric and non-skewed distribution that are symmetrical until the second order, if we fit our data with the normal distribution we observe that the tails are too heavy to create a good fit. Instead, a student-t function fit turns out to address these issues with a coefficient of *ν=2.88±.02, R2=0.9958, RMSE=0.0467ms*

$\nu = 2.88 \pm .02, R^2 = 0.9958, RMSE = 0.0467 \frac{m}{s}$. Based on this, we can still continue with the same equation 8, where we can now determine the mean horizontal deviation *σ horz=νν-2=1.81* $\overline{\sigma_{horz}} = \sqrt{\frac{\nu}{\nu-2}} = 1.81$. Which seems to be to be independent of height. This proves that our rough upperbound still holds. **Addressed in the manuscript as such:** "The difference in power due to this non-linearity is given in 8: P_turbulence=(P(v+σ_horz)+P(v-σ_horz))/2-P(v)=3/2 ρ A v σ_horz^2>0 (8) It should be noted that only a part of this turbulence kinetic energy can be transferred to the blades and therefore this value can only be used as an upper-bound. Additionally, this equation assumes that the wind speed deviations to the mean wind speed are symmetrical until the second order, the turbulence power can be considered only as a rough upper-bound to the influence of turbulence on the wind turbine performance. The assumption that the wind speed deviations from the mean is symmetrical to the second order can be validated by considering the 1-second wind speed data measured by the WindCube throughout the campaign. The distribution is symmetrical to the second order and can be fitted with a student-t distribution which exhibits these symmetries, with ν=2.88±0.02, R^2=0.9958."

1. Figures 7, 9, 10, 11 are blurry, please increase the figure resolution.

We have addressed figure quality.

Competing Interests: No competing interests were disclosed.

Reviewer Report 11 February 2025

https://doi.org/10.21956/openreseurope.20665.r50315

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Norman Wildmann
Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany

Van Schaik et al. present an experimental study which utilizes one lidar of type Windcube v2.1 to measure wind profiles at an Alpine pass at different locations. The topic is relevant, since complex terrain flow effects are critical for wind energy siting and many uncertainties remain. I disagree with the authors that their method of sequential lidar scans was shown to be effective for site assessment in this study. The study touches a lot of interesting topics, but lacks a clear focus and in depth analyses of specific results. It is shooting very high with very general goals, but cannot convincingly show the value of the results. I recommend to reconsider the goals, restructure and resubmit a more focused study which can be backed up with the measurements that are present. General and specific comments are given below. I recommend to reject the manuscript at this point.
General comments
- It should be made more clear in the introduction what the actual goal is of the measurements. You could describe what is the standard procedure for WEA, how long the requirements are for instrument deployment and statistics of wind sectors t benchmark your results with. If wind resource assessment is the goal, than I get the impression that the database is much too small and the sequential lidar transects fails to provide the necessary information. If the goal is to study specific flow conditions, I would expect more of a focus on specific situations and some numerical simulations to accompany the measurements.
- The experimental setup is flawed from my perspective because there is no reference to benchmark the results with. I think it would have been important to have at least one lidar continuously at one position. A CFD model to simulate specific wind conditions and check if matching different situations is appropriate could also be applied, but is not provided. Atmospheric stability is not measured at all, but is crucial.
- The method section is not well introduced and the purpose for the whole wind speed matching remains very unclear when it is first introduced and is not well explained. The equations are unprecise and variable names are not well introduced.
- The way I understand the matching algorithm, two situations are considered the same if wind vectors are within a certain margin, but that is not a full description of the flow.
- Figures are of bad quality (low resolution). The captions are not describing the figures well.
- Equations are not well explained and variables not described.
- The structure of the manuscript is not consistent jumping back and forth between methods, results, definition of goals. There is no clear story-line.
- Many statements and references are unprecise and sometimes even wrong. The authors should carefully revise the text.
- Drawing conclusions from wind profiles that are put together from different days and conditions, just matched by wind speed at hub height can be extremely misleading.
- The manuscript is provided in a format which is hard to review (2 columns, no line numbers, etc.). That is maybe not the authors fault, but editors should consider to change the format.
Specific comments:
p.4, paragraph 1: There are clear definitions for terrain complexity in the IEC 61400. It is probably

good to elude a bit on that in the introduction and make clear that the complexity in this study is of the highest complexity (I assume)
p.4, paragraph 1: "influencing the performance of wind turbines by reducing or augmenting their efficiency". That sentence is not giving much information
p.4, 2nd column 2nd paragraph: "airborne lidar" - that is not correct. There was no airborne lidar measuring wind transects across the valley at Perdigao.
p.4, 2nd column 2nd paragraph: simulations cannot prove the validity of lidar measurements and were not used for that purpose in the referenced studies.
p.4, 2nd column 3rd paragraph: WEAs operate lidars to perform WEA? that is a weird construction
p.7, 2nd column "Lidar details": The range gate increments was already introduced in the chapter before. It may make sense to move this section before the explanation of the sequential Instrumentation overview.
p.9, 1st column, 2nd paragraph: why is the temperature sensor at 1m? Usually 2m is a standardized height for such measurements.
p.9, Eq.1 etc.: At this point in the manuscript it is unclear why you want to calculate the difference of all 10-minute wind speeds for the five turbines
p.10, Fig.6: the resolution of this figure is very low and texts are hard to read.
p.11, right column, 2nd paragraph: pressure, temperature and humidity are not shown in this manuscript though, right? Which instrumentation is used to check it? Are there any measures for stability? How the flow develops along the transect is surely dependent on stability.
p.11, right column, "Results": are Fig.6&7 not already results?
p.11, right column, last paragraphs: why are these paragraphs italic? where do they belong to?
p.13, Table 3: why not show the distributions?
p.11, "above rated wind speed": the wind roses do not distinguish between above and below rated wind speed, the upper bin is >8m/s, but rated wind speed is 11m/s.
p.12, Figure 8: What are turbines A-E? So far they were referenced with numbers 1-5 or T1-T5. Please be consistent or describe in the caption.
p.13, Figure 9: The caption should be more descriptive about what the colors and arrows mean.
p.13, right column, first paragraph: If you see a flow acceleration between the position, how can you be sure that acceleration effects are not also present at hub height and would this not be a problem for the wind matching? You actually match conditions which are very different.
p.14, Figure 11: The figure clearly shows that for positions L4 and L8 there was strong shear and veer, thus a very different flow condition than for the other positions. How can you put these conditions together? It does not make sense.
p.14, right column, last paragraph: I cannot believe that the shear and veer at a specific location is independent of atmospheric stability.
p.15, Table 4: the table shows that wind profiles of early morning, early afternoon and late afternoon are mixed.
p.17, Fig.14: what are the axis of those TKE distribution plots?
p.16, "Turbulence kinetic energy": This Section is premature. You cannot make statistics of TKE with this database and calculate effects on power production the way it is done here. The references are wrong too. Reference 8 does not provide Eq. 8. I recommend to have a close look at the IEC 61400 standards.
p.19, Fig.15: What is the normalized power production. There should be an equation somewhere.
p.19, "Sequential vs. Synchronized": This section does not give any new information compared to the introduction and an actual comparison cannot be made, because data from synchronized lidars is not available in this campaign.
p.19, "Conclusion": "a novel method for high-resolution, three-dimensional wind profile

measurements" - I disagree. The data presented here is not "high-resolution three-dimensional" It is standard wind profiles with Windcube v2.1. for short time periods at different locations.
p.20, second paragraph: I disagree that the matching algorithm is successful. The analyses show that just matching the wind speed at hub height is not enough to describe a common flow situation in such complex environment. Actually it is misleading to suggest it does.

Is the work clearly and accurately presented and does it cite the current literature?
No

Is the study design appropriate and does the work have academic merit?
No

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
No

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: boundary-layer meteorology, lidar measurements, complex terrain, wind energy

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

Author Response 11 Nov 2025

Brandon van Schaik

Norman Wildmann

- It should be made more clear in the introduction what the actual goal is of the measurements. You could describe what is the standard procedure for WEA, how long the requirements are for instrument deployment and statistics of wind sectors t benchmark your results with. If wind resource assessment is the goal, than I get the impression that the database is much too small and the sequential lidar transects fails to provide the necessary information. If the goal is to study specific flow conditions, I would expect more of a focus on specific situations and some numerical simulations to accompany the measurements.
R: The section title of Methods was misplaced in this draft which meant that a large part of

the introduction was actually displayed as the start of the introduction. We have indicated this to be changed to the correct position in the next iteration. Regarding the clarity of the goals, it is **addressed in the manuscript as such:** "This work serves as a proof of concept and as a preliminary showcase of the unique data sets and analyses that are unlocked by the sequential LiDAR experimental methodology, enabling the high-resolution study of the three-dimensional wind over the entire wind park domain.". In response to this comment, and those made by another reviewer, we have complemented the LiDAR observations with additional CFD simulations covering the full 3-month campaign period and the entire mountain pass. These simulations provide spatially and temporally continuous wind fields that support the short-term measurements. Specifically, we have identified 8 characteristic features including, global horizontal irradiance, atmospheric stability, vertical shear magnitude, variance of the vertical turbulence, an average of the transect wind field, and the synoptic wind at 5km. To this end, the Methodology section is completely overhauled and Results updated accordingly. We believe this addresses the reviewer's concern by providing a more complete picture of the wind conditions across all sites.

- The experimental setup is flawed from my perspective because there is no reference to benchmark the results with. I think it would have been important to have at least one lidar continuously at one position. A CFD model to simulate specific wind conditions and check if matching different situations is appropriate could also be applied, but is not provided. Atmospheric stability is not measured at all, but is crucial.
R: Thanks to your suggestions we have opted to provide additional CFD simulations to help contextualize the turbine wind vector matching algorithm. We have updated the matching algorithm as elaborated in the previous comments. We refer to the Methodology section of the manuscript for the detailed overview of the 8 characteristic features that are now implemented.

- The method section is not well introduced and the purpose for the whole wind speed matching remains very unclear when it is first introduced and is not well explained.
R: The equations are unprecise and variable names are not well introduced. To make this transition to the Methodology more clear, as well as to introduce the idea of the wind speed matching immediately, we have moved the LiDAR details to the instrumentation section. We have improved equations and variables and completely overhauled the Methodology section to include the 8 CFD characteristic features. We believe this overhaul has greatly improved the flow of this section.

- The way I understand the matching algorithm, two situations are considered the same if wind vectors are within a certain margin, but that is not a full description of the flow.
R: We have updated the matching algorithm as elaborated in the previous comments. We refer to the Methodology section of the manuscript for the detailed overview of the 8 characteristic features that are now implemented.

- Figures are of bad quality (low resolution). The captions are not describing the figures well.
R: Figure quality has been addressed. We are limited to 15 words per caption by the journal, we have optimised captions within this limit.

- Equations are not well explained and variables not described.

R: We have checked all equations and verified that variables are introduced and described.

- The structure of the manuscript is not consistent jumping back and forth between methods, results, definition of goals. There is no clear story-line.
R: We have updated the matching algorithm as elaborated in the previous comments. We refer to the Methodology section of the manuscript for the detailed overview of the 8 characteristic features that are now implemented.

- Many statements and references are unprecise and sometimes even wrong. The authors should carefully revise the text.
R: We assume said statements and references are described in the reviewer's specific comments. We have addressed those below.

- Drawing conclusions from wind profiles that are put together from different days and conditions, just matched by wind speed at hub height can be extremely misleading.
R: We have updated the matching algorithm as elaborated in the previous comments. We refer to the Methodology section of the manuscript for the detailed overview of the 8 characteristic features that are now implemented.

- The manuscript is provided in a format which is hard to review (2 columns, no line numbers, etc.). That is maybe not the authors fault, but editors should consider to change the format. **R:** We thank the reviewer for pointing this out. The manuscript format is determined by the journal's submission system, and unfortunately we do not have direct control over line numbering or layout. We trust that the editorial office will take this into consideration.

Specific comments:

p.4, paragraph 1: There are clear definitions for terrain complexity in the IEC 61400. It is probably good to elude a bit on that in the introduction and make clear that the complexity in this study is of the highest complexity (I assume)
R: We appreciate the reviewer's suggestion. While the IEC 61400 provides clear definitions for terrain complexity, it is not an open-access document, and therefore we have chosen not to cite it directly. Nonetheless, we agree that the terrain in our study area qualifies as highly complex according to commonly used classifications. We have clarified this in the revised introduction to better frame the context of our work, without relying on proprietary standards. **Addressed in the manuscript as such:** "The Gotthard Wind Park can be categorised as the highest degree of complex terrain for wind energy development, characterised by large elevation changes, up- and downwind valleys and steep escarpments within the wind park itself."

p.4, paragraph 1: "influencing the performance of wind turbines by reducing or augmenting their efficiency". That sentence is not giving much information
R: Addressed in the manuscript as such: "influencing the performance of the wind turbine by the non-idealised wind flow into the turbine."

p.4, 2nd column 2nd paragraph: "airborne lidar" - that is not correct. There was no airborne

lidar measuring wind transects across the valley at Perdigao.
R: We thank the reviewer for catching this mistake. The reference to “airborne lidar” was incorrect and has been removed. It was a confusion with the airborne surface scanning LiDAR used at Perdigão.

p.4, 2nd column 2nd paragraph: simulations cannot prove the validity of lidar measurements and were not used for that purpose in the referenced studies.
R: Addressed in the manuscript as such: “establishing the use of LiDAR measurements as a valid wind assessment tool over a wide range of spatial resolutions.”

p.4, 2nd column 3rd paragraph: WEAs operate lidars to perform WEA? that is a weird construction
R: “WEAs rarely operate more than one LiDAR to perform a wind energy assessment.”
Replaced by: “WEA studies rarely operate more than one LiDAR”

p.7, 2nd column "Lidar details": The range gate increments was already introduced in the chapter before. It may make sense to move this section before the explanation of the sequential Instrumentation overview.
R: Thank you for the helpful suggestion, we have adopted this in the revision.

p.9, 1st column, 2nd paragraph: why is the temperature sensor at 1m? Usually 2m is a standardized height for such measurements.
R: Out of practical reasons this was done. A one metre rebar pole could be easily hammered into the soil. Longer poles to mount the sensor at 2m would require guywires which was not always possible in the terrain. Since the LiDAR was moved every week, this was not practical. Since the surface topography is free of brushes and rocks, this difference should not impact the variances in the temperature readings much. Particularly since we average over 10min intervals. Since the temperature is only used for air density calculations in which the temperature only has a small sensitivity, we do not see a reason to distrust the accuracy of this data. **Addressed in the manuscript as such:** “A radiation-shielded combined pressure, temperature, and humidity sensor was placed near the LiDAR 1 m above the ground which is solely used to calculate the local air density.”

p.9, Eq.1 etc.: At this point in the manuscript it is unclear why you want to calculate the difference of all 10-minute wind speeds for the five turbines
R: With the additional CFD simulations methods in the manuscript, this has been addressed accordingly. We have also introduced the goals more clearly, and earlier in the manuscript.

p.10, Fig.6: the resolution of this figure is very low and texts are hard to read.
R: All figures have been replaced with higher-resolution versions in the revised manuscript. In addition, Figure 6 is no longer included, as it became irrelevant following the revisions to the Methodology section and has been removed.

p.11, right column, 2nd paragraph: pressure, temperature and humidity are not shown in this manuscript though, right? Which instrumentation is used to check it? Are there any measures for stability? How the flow develops along the transect is surely dependent on stability.

R: We only use pressure temperature and humidity to calculate the average air density over the whole campaign. We mention the existence of this sensor as it is included in the data set that is co-published with this paper. The sensor in use is the standard PTH sensor provided by VAISALA for the WindCube v2.1. More details are now given in the instrumentation table (Table 1). Atmospheric stability is now addressed with CFD simulations. We refer the reviewer to our reply of his first comment as well as the Methodology section of the revised manuscript for the full details.

p.11, right column, "Results": are Fig.6&7 not already results?
R: These figure have become irrelevant following the revisions to the Methodology section and have since been removed.

p.11, right column, last paragraphs: why are these paragraphs italic? where do they belong to?
R: We thank the reviewer for noting this editing error. The paragraphs are now placed correctly in the revised manuscript.

p.13, Table 3: why not show the distributions?
R: In our view, the distributions are not directly relevant to the goals of the study. Presenting the results in tabular form provides a more space-efficient and quantitative summary, allowing readers to readily compare the two wind directions as well as reproduce/refer to the data immediately.
p.11, "above rated wind speed": the wind roses do not distinguish between above and below rated wind speed, the upper bin is >8m/s, but rated wind speed is 11m/s.
R: Excellent suggestion, the wind roses are updated to reflect the different stages in the E-92 power curve, and the figure has been updated.

p.12, Figure 8: What are turbines A-E? So far they were referenced with numbers 1-5 or T1-T5. Please be consistent or describe in the caption.
R: Combined with the previous comment, we have adapted this as well in the figure.

p.13, Figure 9: The caption should be more descriptive about what the colors and arrows mean.
R: We are limited to 15 words per figure/table caption by the journal regulations. We have described this in more detail in the text. We have also added a legend to explain the difference in colours. Besides, this figure has been replaced due to the improved methodology as suggested in your earlier comments. We refer the reviewer to the Transect wind profile evolution and Wind shear and veer subsections in the results for our improved results.

p.13, right column, first paragraph: If you see a flow acceleration between the position, how can you be sure that acceleration effects are not also present at hub height and would this not be a problem for the wind matching? You actually match conditions which are very different. **R:** We have updated the matching algorithm as elaborated in the previous comments. We refer to the Methodology section of the manuscript for the detailed overview of the 8 characteristic features that are now implemented. This flow acceleration can now be identified using by CFD simulation characteristic features: “Vertical shear magnitude”,

"Variance of the vertical turbulence", and "Transect-averaged wind". We refer the reviewer to the Transect wind profile evolution and Wind shear and veer subsections in the results for our improved results.

p.14, Figure 11: The figure clearly shows that for positions L4 and L8 there was strong shear and veer, thus a very different flow condition than for the other positions. How can you put these conditions together? It does not make sense.
R: We have updated the matching algorithm as elaborated in the previous comments. We refer to the Methodology section of the manuscript for the detailed overview of the 8 characteristic features that are now implemented. This shear/veer concern can now be identified using by CFD simulation characteristic features: "Vertical shear magnitude", "Variance of the vertical turbulence", "Global Horizontal Irradiance", "Atmospheric stability", and "Synoptic wind at 5km". We refer the reviewer to the Transect wind profile evolution and Wind shear and veer subsections in the results for our improved results.

p.14, right column, last paragraph: I cannot believe that the shear and veer at a specific location is independent of atmospheric stability.
R: We have updated the matching algorithm as elaborated in the previous comments. We refer to the Methodology section of the manuscript for the detailed overview of the 8 characteristic features that are now implemented. This shear/veer and atmospheric stability concern can now be identified using by CFD simulation characteristic features: "Vertical shear magnitude", "Variance of the vertical turbulence", and "Atmospheric stability". We refer the reviewer to the Transect wind profile evolution and Wind shear and veer subsections in the results for our improved results.

p.15, Table 4: the table shows that wind profiles of early morning, early afternoon and late afternoon are mixed.
R: We have updated the matching algorithm as elaborated in the previous comments. We refer to the Methodology section of the manuscript for the detailed overview of the 8 characteristic features that are now implemented. This time of day mixing can now be identified using by CFD simulation characteristic features: "Global Horizontal Irradiance", and "Atmospheric Stability" We have consequently updated the table to address the stricter matching protocol discussed in the overhauled Methodology section.

p.17, Fig.14: what are the axis of those TKE distribution plots?
R: We have revised the captions to clarify that the plots represent probability density functions of the TKE. The as the exact values of TKE are not directly relevant for our conclusions, and for clarity we therefore choose to not include x ticks or y ticks. Since our caption size is limited, we have updated the manuscript section in which the figure is first referred to as shown below. The plots are intended to highlight relative differences, and since all TKE distributions share identical x-limits, they can be visually intercompared as discussed in the manuscript. **Addressed in the manuscript as such:** "This bi-model distribution is similar to the wind speed, along the LiDAR transect as shown in Figure 12. In these figures, the red lines represent the probability density functions of the TKE, while the blue vertical lines indicate the mean TKE, allowing for a visual identification of where turbulence is strongest along the transect."
p.16, "Turbulence kinetic energy": This Section is premature. You cannot make statistics of

TKE with this database and calculate effects on power production the way it is done here. The references are wrong too. Reference 8 does not provide Eq. 8. I recommend to have a close look at the IEC 61400 standards.
R: We thank the reviewer for this valuable comment. We have revised the section to clarify that our analysis is not intended as a full turbulence kinetic energy (TKE) assessment, but rather as a simplified approach to provide a rough upper bound on the potential influence of turbulence on turbine performance. We now emphasize that Eq. (8) is a first-order approximation based on the curvature of the power curve and assumes symmetric fluctuations up to second order. Furthermore, we have verified the applicability of Eq. (8) using our 1-second LiDAR data, which shows that the deviations from the mean are approximately symmetric and can be fitted by a Student-t distribution. This supports the use of Eq. (8) as a conservative upper-bound rather than a precise quantification. Finally, we have corrected the references and added a note pointing the reader to the IEC 61400 standards, which provide the proper framework for turbulence intensity and load assessments. **Addressed in the manuscript as such:** "Equation 8 provides a first-order estimate of how turbulence around the mean affect turbine power output: Equation 8 *P turbulence=Pv+σhorz+Pv-σhorz2-Pv=32ρ A v σhorz2>0*

$P_{turbulence} = \frac{P(v+\sigma_{horz})+P(v-\sigma_{horz})}{2} - P(v) = \frac{3}{2}\rho A v \sigma_{horz}^2 > 0$ However, the actual effect of turbulence is governed by the curvature of the turbine power curve: In convex sections of the power curve, positive and negative fluctuations are weighted asymmetrically, leading to a net increase in power relative to the mean wind speed. Whereas in concave sections, the reverse occurs and fluctuations produce a net decrease in power. Therefore Equation 8 represents only a rough upper-bound to the influence of turbulence on power production. It does not account for the changing curvature of the real power curve, nor for higher-order asymmetries in the wind speed distribution. For a full quantification, we refer the reader to a work that integrates the measured wind speed probability density function and other vertical variations with the actual turbine power curve as referred to in international standards. Furthermore, we have validated the assumption of second-order symmetry in the wind speed variations measured the Doppler wind LiDAR. The 1-second wind speed data from the WindCube during the campaign shows that the deviations from the mean are not perfectly normally distributed. They rather remain symmetric up to second order and an be fitted optimally with a Student-t distribution (ν=2.88±0.02, $R2$=0.996 $\nu = 2.88 \pm 0.02, R^2 = 0.996$), which captures the heavy tails observed. From this the mean horizontal deviation can be expressed as $\sigma horz=v/(\nu-2)$ =1.81 $\sigma_{horz} = \sqrt{\nu/(\nu-2)} = 1.81$, Which seems to be independent of height. Which consequently validates that the rough upper-bound still holds."

p.19, Fig.15: What is the normalized power production. There should be an equation somewhere.
R: Addressed in the manuscript as such: "The power production is normalised to 7 ms^(-1) 7 m/s by the cubic relation between power and wind speed in this range with Equation 9. Equation 9 *Pnormalised=PvCp(7ms-1)7 ms-13Cp(v)v3, 4 ms-1*≤v≤10 m*s-1*

$P_{normalised} = P(v)\frac{C_p(7ms^{-1})(7\ ms^{-1})^3}{C_p(v)v^3}, 4\ ms^{-1} \le v \le 10\ ms^{-1}$ "

p.19, "Sequential vs. Synchronized": This section does not give any new information compared to the introduction and an actual comparison cannot be made, because data from synchronized lidars is not available in this campaign.
R: We have conducted additional CFD simulations to address this concern, as outlined in our earlier responses. We believe that these methodological adaptations improve the robustness of the results and provide sufficient support for our conclusions in this section.

p.19, "Conclusion": "a novel method for high-resolution, three-dimensional wind profile measurements" - I disagree. The data presented here is not "high-resolution three-dimensional" It is standard wind profiles with Windcube v2.1. for short time periods at different locations.
R: We thank the reviewer for this comment. While we agree that standard WindCube v2.1 instruments provide vertical wind profiles at single locations, our methodology goes beyond this typical use. By deploying the lidar sequentially along a dense transect with 150 m horizontal spacing and 10–20 m vertical resolution, we obtain a high-resolution, three-dimensional reconstruction of the wind field across complex terrain. Something that cannot be achieved with a single lidar in a fixed location. Furthermore, the newly added CFD simulations now support and address the reviewer's concerns about temporal discontinuity and the matching algorithm. Therefore, we believe that the description of the method as "high-resolution, three-dimensional wind profile measurements" is appropriate in the context of this study.

p.20, second paragraph: I disagree that the matching algorithm is successful. The analyses show that just matching the wind speed at hub height is not enough to describe a common flow situation in such complex environment. Actually it is misleading to suggest it does.
R: The newly added CFD simulations help address the reviewer's concerns regarding temporal discontinuity and provide validation for the adapted matching algorithm. We therefore consider the revised algorithm to be appropriate and effective for the purposes of this study.

Competing Interests: No competing interests were disclosed.