A Field Validation Study of Mass-conserving and 3D Linear Wind Modelling at Blackford Hill, Edinburgh

Rhodri Herapath[1], Zain Alaf Ul Mulk[1], Yijie Wang[1], Samuel Sancar[1], Richard Essery[1†]

[1] School of Geosciences, University of Edinburgh

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Abstract

Assessments of the effect of terrain roughness on the flow of wind are essential in planning for civil engineering works, wildfire fighting, aviation, forecasting and in the energy transition, for which computational fluid dynamics derived diagnostic, and linear fluid flow models have been developed. An assessment of the turbulent wind flow over an isolated hill of high surface roughness (Blackford Hill, Edinburgh) has been conducted and a comparison between field anemometry and linear fluid flow, as well as outputs from the U.S. Department of Agriculture Forest Service's mass-conserving WindNinja model, has been made. The wider area around Blackford Hill presents a surface of high roughness, representative of a semi-urban environment and forming an ideal location to test model specificities and performance in varied prevailing wind conditions. Correlation of the net wind speed, as it is perturbed by topography relative to wind speed in the surrounding terrain, between measurements and both models is generally poor, owing to short averaging times, as well as model and methodological limitations in the case of this experiment. Both WindNinja and linear model outputs present greater correlation with field measurements for westerly wind profiles than easterly. Wind direction at the summit as it is perturbed by topography is generally better predicted by both methods with little difference from measured prevailing wind direction on respective days of measurements. Modelling of flow in upwind profiles and at the crest of the hill for both methods is generally more robust, though some significance for linear model predictions in the lee has been demonstrated for certain wind directions.

Introduction

Accurate prediction of near-surface wind flow over complex terrain is important for applications including civil engineering, aviation, wildfire management, weather forecasting, and renewable energy planning. Terrain roughness and topographic complexity strongly influence wind speed and direction by modifying atmospheric flow (Ngo *et al.* 2008; Zou *et al.* 2022; Wang *et al.* 2025), making their accurate representation essential for reliable wind prediction. Consequently, both computational fluid dynamics (CFD) models and linear flow models have been widely developed and applied to simulate wind flow over complex landscapes.

Previous studies have demonstrated that CFD-based and parametrised approaches (Blocken *et al.* 2015; Helbig *et al.* 2017; Wang *et al.* 2025) can improve the representation of terrain-induced flow features, while linear models provide computationally efficient alternatives for many operational applications. WindNinja, a mass-conserving CFD model developed for wildfire applications, has been shown to improve mesoscale, synoptic-forced wind forecasts compared with the NOAA High Resolution Rapid Refresh model (Seto *et al.* 2025). Conversely, both CFD and linear models have exhibited larger directional-dependent errors when applied within urban or highly rough terrain environments (Byrne *et al.* 2021). Earlier field studies have also evaluated wind modelling over locations such as North Berwick Law and Ailsa Craig. Relatively few studies, however, have compared CFD and linear modelling approaches against extensive in situ observations collected within semi-urban, high-roughness terrain rather than solely over isolated hills using multiple measurement systems (Blocken *et al.* 2015).

This study addresses this gap by evaluating the performance of CFD and linear wind flow models against field measurements collected at Blackford Hill, located within the Hermitage of Braid and Blackford Hill Local Nature

†Corresponding academic contact: Richard.Essery@ed.ac.uk

Reserve in southern Edinburgh. Blackford Hill reaches an elevation of 164 m, has a characteristic horizontal length scale of approximately 650 m, and contains multiple knolls, rocky outcrops, and extensive vegetation, providing a representative example of complex, high-roughness terrain. The study investigates how accurately each modelling approach reproduces observed wind speeds across this environment.

Wind speeds were measured using handheld three-cup anemometers, which convert cup rotation into wind speed through a calibration constant, together with a Kestrel weather station that recorded minute-by-minute wind speed and wind direction. The observational dataset was compared with predictions from the three-dimensional linear model of Walmsley *et al.* (1982), which extends the formulations of Jackson *et al.* (1975) and Mason *et al.* (1979), using a LiDAR-derived Digital Terrain Model (DTM). Model performance was also evaluated using WindNinja (Forthofer *et al.* 2014), an open-source mass-conserving CFD solver. WindNinja has previously demonstrated increased accuracy on the windward side of terrain features (Forthofer *et al.* 2014; Wagenbrenner, Forthofer, Page, *et al.* 2019). We aim to assess performance on both windward and leeward slopes and further perform the analysis on the linear model output.

The remainder of this paper describes the linear and CFD modelling approaches, outlines the field measurement methodology, presents the observational and modelling results, and discusses the performance of each model over complex, semi-urban terrain.

Methods

Theory

We begin with the required form of the Navier-Stokes equation (Stokes 1845), which serves to describe the flow of an incompressible, viscous fluid:

$$\frac{\partial \overline{u}}{\partial t} + \overline{u} \cdot \overline{\nabla}\overline{u} = -\frac{1}{\rho}\overline{\nabla}p + v\nabla^2\overline{u} + \overline{g}$$

Using dimensionless variables (including the dimensionless gradient operator $\boldsymbol{\nabla}$) that are functions of typical length, L, speed, U, and time, t, scales, as well as air pressure, p, density, ρ, of turbulent eddies within the locality and the 3D velocity vector, $\overline{u}$:

$$\overline{\boldsymbol{u}} = \frac{\overline{u}}{U},\ \boldsymbol{t} = \frac{t}{L/U},\ \boldsymbol{p} = \frac{p}{\rho U^2},\ \boldsymbol{\nabla} = L\nabla$$

where $L\nabla$ is a vectorised form of the derivative operator scaled for dimensionless space. We define

$$\frac{\partial \overline{\boldsymbol{u}}}{\partial \boldsymbol{t}} + \overline{\boldsymbol{u}} \cdot \overline{\boldsymbol{\nabla}}\overline{\boldsymbol{u}} = -\overline{\boldsymbol{\nabla}}\boldsymbol{p} + \frac{1}{Re}\boldsymbol{\nabla}^2\overline{\boldsymbol{u}} + \frac{1}{Fr^2} \quad (1)$$

for 3D velocity vector $\overline{\boldsymbol{u}}$. Generally, Equation 1 is a non-linear PDE with 3 equations for 4 unknowns and is unsolvable unless for approximate, specific or otherwise simplified scenarios.

The Reynolds (Re; Thompson 1975) and Froude (Fr) numbers provide measures of the influence of viscosity and of gravity on the flow of the fluid respectively. At Reynolds numbers up to the high 100s, flow is considered to be laminar. At high Reynolds numbers, viscosity can be ignored, though flow is now defined as turbulent and this can affect many wind speed measurements per a point-by-point basis, even if measurements are taken accurately and with little time interval. A low Froude number (< 1) is usually associated with stable stratified conditions (Hunt *et al.* 1997), with the potential for small perturbation flow from the summit.

The conservation of mass in a given volume of space is directly expressed by the continuity equation

$$\frac{\partial \rho}{\partial t} = -\overline{\nabla} \cdot (\rho\overline{u}) \quad (2)$$

where $\rho\overline{u}$ represents the mass flux flowing in or out of the volume. For air of a speed less than $100\ \mathrm{ms}^{-1}$, (an incompressible fluid), Equation 2 equals 0.

Linear Model

Equations 1 and 2 and their corollaries form the basis of both the linear model and the WindNinja solutions. Per the 2D model, within an inner region of the boundary layer, turbulent eddies respond rapidly to velocity gradients distorted in the vertical plane by an isolated hill (Jackson *et al.* 1975). With a balance of acceleration and stress gradient terms in Equation 1, linearised equations are solved by taking a 2D Fourier transform. The theory is expanded to a third dimension by using a Fourier transform for an infinite domain, periodic in both x and y directions, effectively adding a sideways wind component (Mason *et al.* 1979). The Fourier transform is replaced entirely by a Fourier series (Walmsley *et al.* 1982), using surface elevations defined on an $N \times N$ grid, treating data as a discrete signal representing real, non-analytical, and non-functional-form topography. This does, however, result in a model that is more computationally expensive and features periodic lateral boundary conditions.

WindNinja

WindNinja makes use of a mass conserving (Equation 2) and mass-and-momentum conserving (Equation 1) model solver (Forthofer *et al.* 2014). For a mass-conserving solver, it minimises the change from an initial wind field to an adjusted field (as a result of topography) using the square of the difference in each vector field, subject to conservation of mass and zero velocity normal to surface. For the second case, Equation 1 is solved using complex open-source CFD code, simulating wind flow. To ensure that Equation 1 is solvable, simulated flow is assumed to be steady, viscous, incompressible and turbulent. For the purpose of this experiment, due to computational power limitations, only the WindNinja conservation of mass solver was used.

Experimental Procedure

The process of turning an anemometer count into a readable wind speed was, for calibration constant, C, (derived from a wind tunnel anemometer calibration) and time, t, in seconds over which count is taken: $N_{counts} \times \frac{C}{t}$. On both days of measurements, the kestrel system, acting as a reference wind speed point, was set up at the summit of Blackford Hill, gathering wind speed data in ms^{-1} in 1-minute intervals. An initial correctional measurement over 1 minute was taken with both anemometers at the same location of the kestrel so as to gain a more up-to-date calibration constant, minimising systematic error to a greater degree than a previous wind tunnel calibration. Measurements of counts over one-minute periods were subsequently recorded with the anemometers following a path tracked by GPS, mimicking the contours of the hill. On both days, measurements were categorised as being either on the leeward or windward face. It was necessary to ensure good spacing of points so as to be able to assess as much of the models' coverage as possible. The process of taking a single measurement follows:

1. Hold anemometer just above head height to minimise frictional effect from ground surface
2. Release mechanism and begin count. Simultaneously, begin timer. It is essential that counting is begun on the minute.
3. After 1 minute has passed, stop timer and fix mechanism. Make a note of count, time and location. Reset anemometer and move to new location.

The counts were then normalised by the time-corresponding minutely kestrel measurement to gain a relative wind speed at each point on the hill. Note that access two kestrel systems was available on day two, and the second system was placed slightly down from the summit, toward the leeward slope.

The linear model was smoothed to fit the periodic boundary conditions (see 'Linear Model') by applying a 'Tukey window' a signal processing technique that reduces discontinuities at the edges of a data set through the use of segments of a phase shifted cosine. Both the linear model and WindNinja give an output of relative wind speed and direction due to DTM topography given an input prevailing wind direction. Model outputs were extracted at the location of the kestrel(s) each day and the offset with average kestrel and nearby Automatic Weather Station (AWS) readings were calculated. By taking an average, small scale horizontal shear at the kestrel site was accounted for.

Results

Measurements were taken with a south westerly (225°) and north easterly (55°) prevailing wind on days 1 and 2, respectively, as shown in Figure 1. Both days featured a moderate breeze at the summit of Blackford Hill, with that of the second day being slightly stronger.

Reynolds and Froude Numbers

From Equation 1, we calculate the turbulent properties of flow in the system. With a length scale of ≈ 600 m, a velocity scale of $\approx 10\ \mathrm{ms}^{-1}$ and given a kinematic viscosity $v = \frac{\mu}{\rho}$ for a corresponding dynamic viscosity $\mu =$

1.8×10^{-5}kg m^{-1} s^{-1} for air at standard atmospheric temperature and pressure, we return (for air of 1.225 kg m^{-3}):

$$Re = \frac{LU}{v} = 4.1 \times 10^9.$$

Similarly, given a boundary layer of depth ≈ 600 m and eddy size scale 300 m, we return

$$Fr = \frac{U}{\sqrt{gL}} = 0.1.$$

This indicates turbulent air flow and relatively neutrally stratified air with little vertical mixing.

Experimental Results

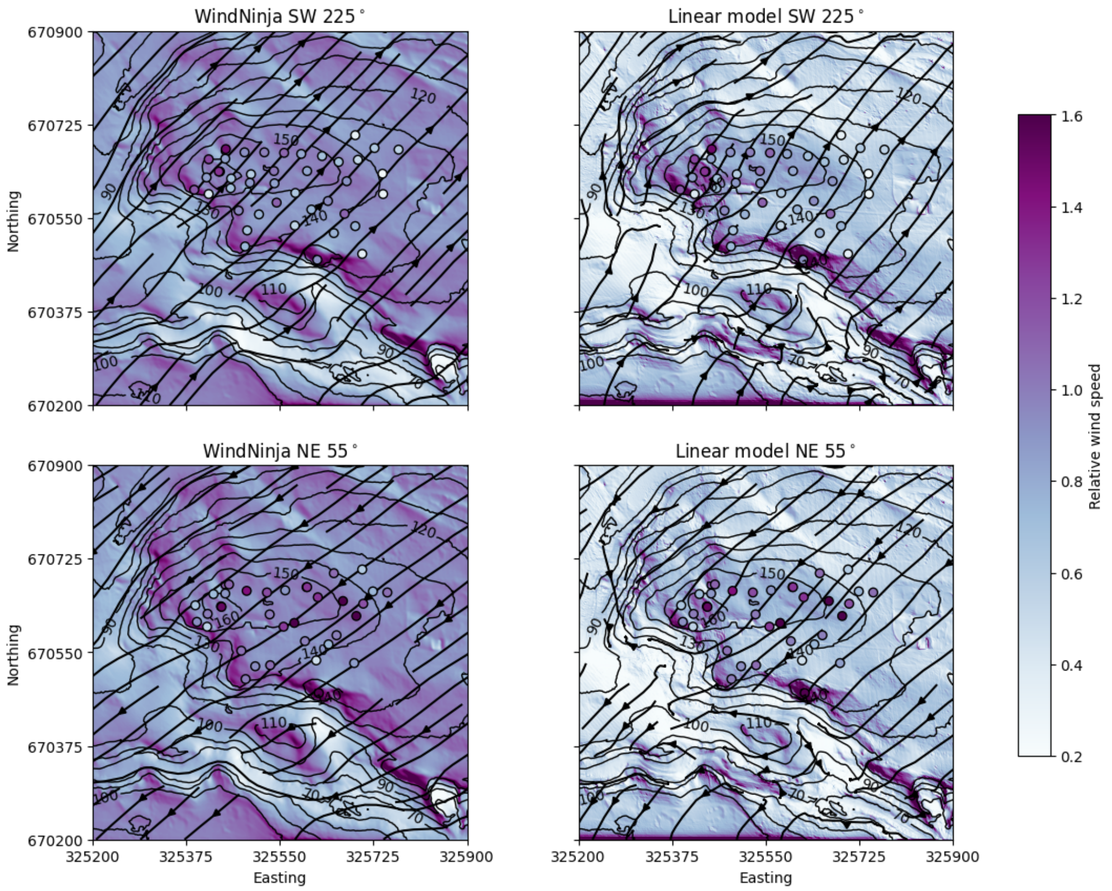

Figure 1: WindNinja and linear model wind fields over Blackford Hill DTM overlaid by field anemometry-derived wind speeds normalised by time-corresponding kestrel reading per day of measurements. All values are on the same colour scale and represent (relative-to-summit) wind speed values that arise as a result of topographic changes. Stream plots indicate respective WindNinja and linear model wind direction.

From Figure 2, low to medium positive correlation with some significance between measurements and both models can be seen on day one, with little to no significant correlation seen on day two. Significance is to 95% confidence interval for the linear model and 90% confidence interval for WindNinja. Anemometer error can be seen to increase with increased wind speed and was taken as a function of instrumental count error propagated through the calibration correction.

Windward vs Leeward Slopes

Windward and leeward slope subsets were used to assess the correlation pattern between measured and WindNinja and linear model derived wind speeds in an attempt to recreate results of previous studies. Note that previous studies only performed this analysis using the mass-conservation solver; we extend this analysis to the linear model.

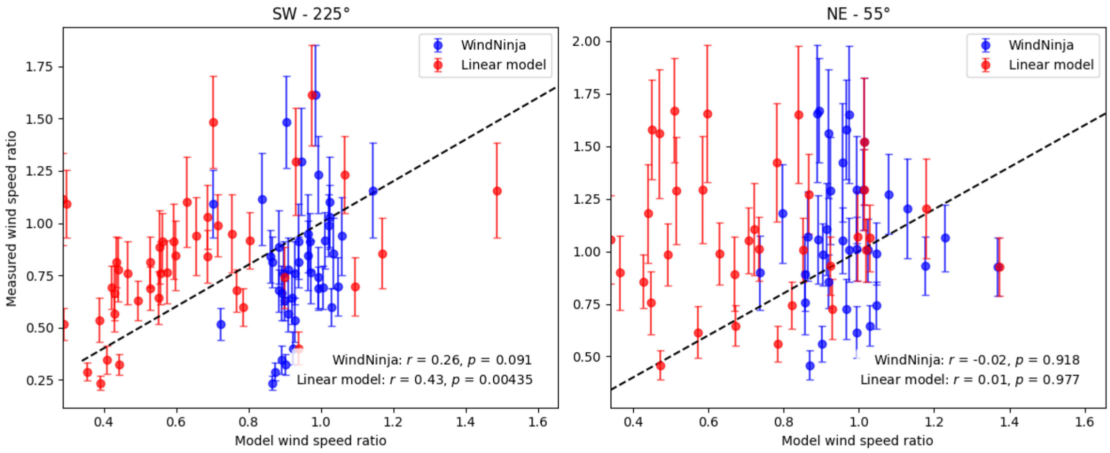

Figure 2: Correlations between between normalised anemometer and model-derived wind speed anomaly due to topography, with anemometer calibration error-bars and reference (theoretical) 1:1 correlation line. Pearson correlation coefficients to examine the linear relationship between measurements and each model have been calculated and are displayed alongside associated p-values.

Figure 3 demonstrates a significant positive correlation (95% CI) between measurements and linear model predictions on the leeward side for a south westerly prevailing wind, though no significant correlation for the corresponding WindNinja prediction. Outwith this result, windward profiles generally present higher correlations with measurements, especially for a south westerly aspect.

Kestrel Measurements

Correlation was calculated between the kestrels for different lengths of time averaging. It is necessary to investigate the assumption that wind speeds measured at different points are perfectly correlated in time, to avoid further uncertainty in comparison between models and measurements. In Figure 4, the correlation initially increases as longer averages were taken, decreases as the number of samples obtained decreases for longer averages.

Wind Direction

	D1	D2
Mean AWS WD (°)	233	55
Mean kestrel WD (°)	231	116
WindNinja WD (°)	230	58
Linear Model WD (°)	243	59

Table 1: Mean kestrel and AWS wind direction (WD), as well as linear model and WindNinja WD extracted from summit easting/northing across days 1 and 2 (D1, D2).

An unusually large difference (Table 1) is observed between kestrel wind direction for day two and other measurements. This is due to the two kestrels having been set out on a 54 degree bearing to follow the flow, with one system fed data from a sheltered position toward the leeward slope and not at the summit. There is a generally small offset between both WindNinja and linear model predicted and AWS measured WD for both days. The offset for day one is 3° for WindNinja and 10° for the linear model. The offset for day two is 3° for WindNinja and 4° for the linear model. Both the WindNinja program and linear model appear to be in agreement for both days, though WindNinja is generally better at predicting wind direction given our prevailing wind readings.

Discussion

There is a large variation in the pattern of correlation between measurements and both models, with positive correlations of statistical significance to at least 90% confidence level for both linear model and WindNinja predictions on day one, with no significant correlation existing between measurements and models on day two. This pattern of correlation is due to natural chaotic variation present within eddies affecting the experiment over 1-minute measurement cycles, model limitations and some terrain roughness effects that will not have been accounted for.

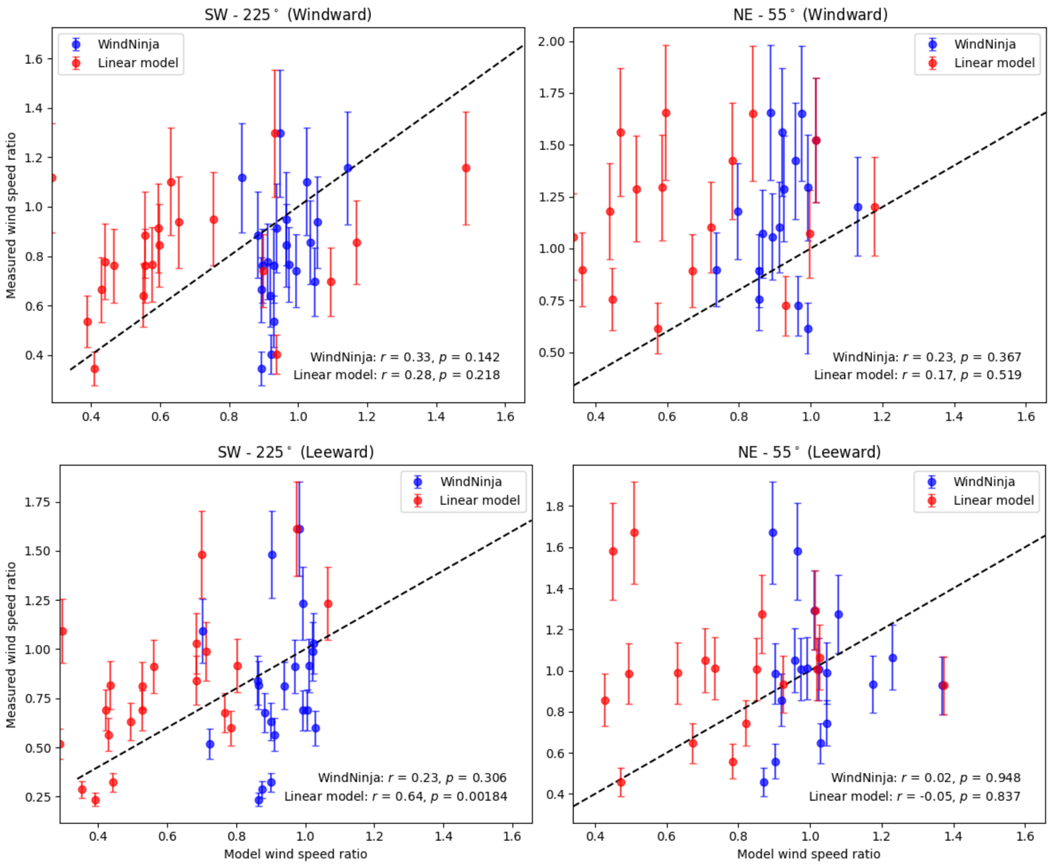

Figure 3: Correlations between normalised anemometer and model-derived wind speed anomaly due to topography, with measurement points separated into windward and leeward hill slopes. As in Figure 2, anemometer calibration error bars and reference 1:1 correlation line are presented. Pearson correlation coefficients to examine the linear relationship between measurements and each model have been calculated and are displayed alongside associated p-values.

The heavy vegetation cover at Blackford Hill, more prominent on the western slopes shown in Figure 1, is likely to introduce a substantial wind-sheltering effect from bushes and trees, reducing measured relative wind speeds at certain data points corresponding to a section of the traverse along a densely bush-lined path. Such terrain roughness features can also create eddies that may affect leeward field measurements on the second day. The eastern slope features less roughness features and will affect leeward measurements to a smaller degree on the first day, providing an explanation for the significance of the respective leeward linear model prediction (Figure 3) though no such significance is noted for the leeward day one WindNinja prediction. With respect to operational sources of error, inaccuracies arise from the anemometer calibration constants, as calibration was performed only once per measurement day, and from timing discrepancies of the order of several seconds between individual readings and the corresponding kestrel measurements. The use of a single one-minute count at each location further introduces random error into the dataset

Model Strengths and Limitations

A marked limitation of the linear model is that for a boundary layer of thickness 600 m, the theory is valid for the case that the ratio of the height and length scales, h and L, satisfies $\frac{h}{L} < 0.05$ though this was validated only for hills with length scales exceeding 1000 m. For Blackford Hill, the corresponding ratio is approximately 0.25, substantially exceeding this threshold. This causes non-linear terms to dominate within the linearisation of the Navier-stokes equation (Equation 1) which may lead to model artefacts such as under-estimation of drag exerted by the hill on the boundary layer, over-estimation of wind speed at the summit, and symmetrical wake patterns down the leeward slope where recirculation zones should exist (Blocken *et al.* 2015; Weerasuriya *et al.* 2016; Patton *et al.* 2026). Moreover, the linear model was developed under idealised assumptions, including neutral thermal stratification, stable mesoscale meteorology, and uniform surface roughness (Jackson *et al.* 1975).

The WindNinja mass-conserving model appears generally unsuitable for predicting wind speeds at Blackford Hill,

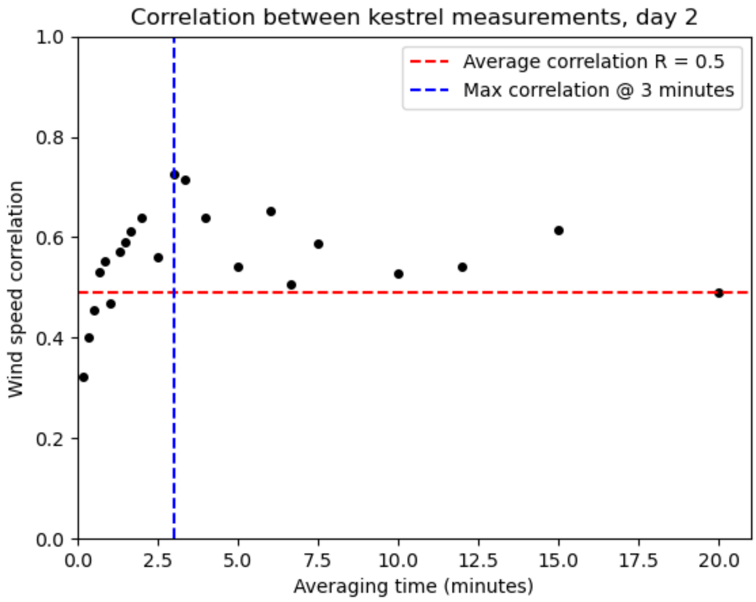

Figure 4: Correlation as a function of averaging time for both kestrels at the summit of Blackford Hill on measurement day two. Maximum correlation is observed at an averaging period of 3 minutes.

whose terrain can be characterised as complex, with high surface roughness. This statement is consistent with Wagenbrenner, Forthofer, Lamb, *et al.* (2016), who evaluated the mass-conserving model using downscaled, high-resolution Numerical Weather Prediction (NWP) winds and reported mixed performance for near-surface wind speed prediction. The model exhibits better performance for upwind profiles than downwind, which has been similarly noted previously (Forthofer *et al.* 2014). Wind direction, by contrast, was found to be more reliably predicted by the software (Wagenbrenner, Forthofer, Lamb, *et al.* 2016), a result corroborated by this study.

Improvements

At shorter averaging times, progressively smaller-scale turbulent eddies exert greater influence on the recorded data. Given the maximum correlation present at around 3 minutes averaging time (Figure 4), and using the average wind speeds measured, it can be assumed that turbulent eddies affecting such measurements were of the order of the 100 m horizontal scale, encompassing the entirety of the locality. Taking measurements over 3-minute intervals therefore would provide an improvement over the 1-minute averaging period used during data collection and smooths recordings containing turbulent spikes of a smaller scale than that of the locality. The possibility of using sonic or electronic anemometers to minimise human error would provide more accurate wind speeds at each point.

The full CFD mass-and-momentum-conservation model solver has been shown to outperform the mass-conservation model solver for both windward and leeward observation locations, with the momentum-conserving solver featuring a more accurate output due to greater consideration of momentum and turbulence on the lee slope (Forthofer *et al.* 2014; Wagenbrenner, Forthofer, Page, *et al.* 2019). Finally we may consider downscaling coarser mesoscale forecast data during model initialisation (Forthofer *et al.* 2014; Seto *et al.* 2025).

Conclusion

A field study utilising anemometry has been conducted to validate the behaviour of the mass-conserving WindNinja and 3D linear model wind vector solvers over Blackford Hill. Flow is of high Reynolds number and low Froude number, while both the linear model and mass-conserving WindNinja solvers appear to show greater accuracy on the windward slopes and crest of the hill, with results appearing to show random behaviour between field anemometer measurements and lee-slope modelling. Potential statistical significance has been demonstrated for correlation between normalised field measurements and both model outputs when considering correlation between between two electronic anemometers using an averaging period of 3 minutes. With current models, it is difficult to predict wind speed over complex terrain such as Blackford Hill. Wind direction has been accurately predicted at the summit of the hill by both models, with WindNinja providing a slightly more robust prediction. There are potential improvements to our methodology, namely longer averaging times over which to take hand measurements and reducing the effects of small scale, short-lived turbulent spikes. Instrumental and human error can be reduced with further automation of anemometers.

Data Availability

Notebooks and associated files used during the experiment and analysis are available on GitHub: https://github.com/herapathr-ux/WindFlow.

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