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Modelling Wind Flow Over Chatham Island

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Abstract

The linearized fluid flow equations used in WAsP may affect its accuracy in areas of complex terrain. A CFD framework was developed in ANSYS CFX to model the fully turbulent flow over complex terrain as an alternative to WasP. Chatham Island was used as a case study when developing this framework. This allowed the CFD model to be validated by comparing simulation results with field data for the wind directions linking two data sources. Following validation, a methodology was developed to estimate the expected power production of the turbines on Chatham Island by using thousands of simulations to represent the full set of wind conditions experienced. The power estimates were compared to power production records obtained from Chatham Island Electricity Limited (CIEL). Although the estimates produced were significantly larger than the output measured by CIEL, adjusting for the effect of operational losses resulted in a close match. The results showed that the CFD framework offered more rigorous analysis of wind flow over complex terrain than linearized approaches while alleviating the computational cost and complexity of full three-dimensional simulations.

Introduction

Wind turbines generated 1600GWh of energy in New Zealand in 2010. By 2014, generation had increased by 34% to 2200GWh [9]. The increasing demand for cost effective, clean, renewable sources of energy has resulted in wind turbines being located in progressively more complex terrains. One such location is Chatham Island. In 2010 two 225kW Vergnet wind turbines were installed on the southwest peninsula of Chatham Island with the aim of reducing the cost of power for the isolated community. Locating wind turbines in a site such as this without accurate estimates of the localised wind climate can result in the inefficient application of capital, disappointing power production and potentially dangerous wind loadings. Currently, the industry standard for wind climate estimation is WAsP which relies on linearized fluid flow equations. In general, these are only applicable to non-detached wind flow [2]. This makes WAsP unsuitable for use at many potentially viable wind turbine locations such as those on Chatham Island. This limited applicability, combined with the challenge of modelling synoptic wind flow and small-scale turbulence, motivates the investigation and development of a CFD framework which can be used to estimate the wind climate at a given location. Chatham Island offers an ideal test case in which to develop and validate a CFD wind climate estimation framework as its relatively small size provides a computationally challenging but resolvable environment. Additionally, there is a reasonable amount of historical data which may be used to assess the accuracy of the framework.

Historical Wind Data

Establishing an accurate estimate of the regional wind climate is a major obstacle faced when modelling the potential wind energy available at a location. 10 years of wind data was obtained from two NIWA climate stations, Tuuta Airport and Waitangi Settlement, to estimate the long term wind flow conditions. Their locations are indicated by the red star and purple circle respectively on Figure 1. This data was sourced from NIWA's national climate database [10] for the period between the 1st of January 2001 and the 1st of January 2011. It included both the average velocity and direction of the wind over three hourly periods at a reference wind height of 2m above the ground. The velocity was measured in metres per second and the direction in degrees from north. The wind bearings were grouped into the 16 main compass directions. The 10 year data sets were compared to data sets spanning 5, 7 and 15 year time periods. This comparison suggesting that 10 years of wind data is sufficient to capture the long term wind climate on Chatham Island.

The Tuuta Airport data set was used to define the probability of different wind flow conditions on Chatham Island. The Waitangi Settlement data was combined with the Tuuta Airport data to provide a validation data set which was used to assess the accuracy of the two-dimensional CFD model.

Energy Generation Data

The turbine operator, Chatham Island Electricity Ltd (CIEL), supplied 12 months of energy production data for the period between July 2013 and June 2014. This data included the total energy generated as well as the total energy supplied to the power network from the two wind turbines. A summary of this data has not been included in this report in accordance with confidentiality agreements. The exact specifications of the turbines, including its power curve, were also provided.

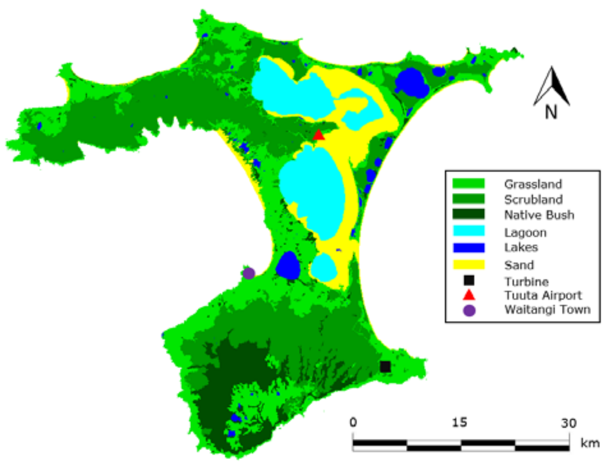

Figure 1. Topographical map of Chatham Island. Data source: LINZ [8]

Topographic Data

Data detailing the surface features of Chatham Island were sourced from Land Information New Zealand (LINZ) [8]. Modelled features included included grassland, native bush, lagoons, lakes, scrub and sand. This data is presented in Figure 1 above. Contour data, used to generate island cross sections, was also sourced from LINZ.

Numerical Modelling Overview

Two sets of two-dimensional simulations were used to estimate the wind flow at the turbine hub. The first set of simulations was centred on Tuuta Airport. The results of these simulations were used to estimate the distribution of the oceanic wind flow conditions and therefore the inflow boundary conditions for the second set of simulations. The second set was centred on wind turbine's location and was used to estimate their power production. The statistical methodology used to estimate the oceanic and turbine hub wind distributions will be discussed in the section Estimating Turbine Power Production below.

45 different characteristic wind velocities were modelled for each of the 16 key wind directions at both Tuuta Airport and the turbines' location. All CFD simulations were run in ANSYS CFX using the k-ε turbulence closure. This turbulence model was selected because it provides significant reductions in computational time required by simulations compared to other methods [7]. The computational domain and model parameters are briefly discussed below. The development of this numeral model is discussed in detail in [1] and [13].

Computational Domain

The two-dimensional domains described above were centred on either Tuuta Airport or the Chatham Island turbines. These domains were discretised using a structured quadrilateral mesh generated in MATLAB. One unique mesh was created for each of the 16 wind flow directions for both locations.

The meshes were each generated with three horizontal regions (inflow, island and outflow) all of which had a height of 1km which was discretised into 100 cells vertically. In all three regions each cell had an exponentially increasing height from an initial height of 1m.

The inflow region was 2km long with 70 cells horizontally. The width of the mesh cells was decreased exponentially from a first cell size of 50m. The outflow region was 4km long with 50 cells horizontally. The width of these cells increased exponentially from an initial size of 50m as the mesh moved away from the island.

Between these two regions there was the island mesh. An algorithm, designed by Beavis [1], was used to adaptively set the island mesh element widths based on the gradient of the island's surface. This resulted in an increased mesh resolution in areas where complex flow was expected. A characteristic mesh is shown in Figure 2. Mesh sensitivity analysis indicated that meshes generated using this methodology provided an acceptable balance between the time taken to run a simulation and its accuracy [1, 3].

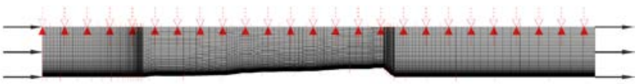

Figure 2. North-easterly mesh generated using the adaptive cell width algorithm

Model Parameters

A library of inflow profiles was developed to describe the atmospheric boundary layer at varying wind speeds over the open ocean [4]. The development of these profiles is discussed in detail by Beavis [1]. Wind flow was always modelled from left to right by using the profiles as inflow conditions to prescribe the velocity, turbulent kinetic energy and turbulent eddy dissipation of the wind flow hitting Chatham Island. A uniform relative pressure condition was applied to the outlet. The surface of Chatham Island was modelled using a fixed, no slip wall. The complex geometries of the island's small scale surface features were represented using a wall function and an effective aerodynamic roughness. These roughness values were prescribed using a function based on the surface feature data provided by LINZ. The aerodynamic roughness lengths of each surface feature are presented in [13] based on research conducted by [5, 12]. A unique boundary function was generated for each simulation. This allowed easy investigation into the effects of surface detail on the wind flow over Chatham Island. These comparisons can be found in Chapter 5 of [13]. Symmetry boundary conditions were applied to the front, back and top boundaries of the domain enforcing zero normal gradient conditions at these points. All simulations were run until the maximum residuals were below $1\text{x}10^{-4}$. Convergence analysis indicated that this was a sufficient tolerance [1].

An example of a characteristic wind flow simulation can be seen in Figure 3 below. Here the velocity contours are shown for a north-west wind flow simulation centred on the turbine. This simulation was run with an inflow profile with a 2m reference velocity of 10.8 m/s.

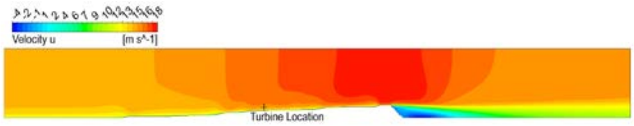

Figure 3. Velocity contours for a Turbine Simulation of north-east wind with an inflow velocity of 10.8 m/s

Automation

The modelling methodology described above was infeasible without automation of the modelling process. PRE and POST scripting tools were used to automatically run the simulations and process their results. Further discussion into the automation of the framework are presented in Chapter 4 of [13].

CFD Model Validation

The performance of the CFD implementation was validated by assessing its ability to correctly model the wind velocity at two different locations. These validation simulations occurred along the island cross-section running through the Tuuta Airport and Waitangi Settlement measurement stations. In addition to having two significant data sources, this cross-section of Chatham Island featured complex terrain. This provided a test of the model's ability to predict the large velocity gradients induced by the complexity of the terrain. The methodology and results of this process are discussed below. It was necessary to filter the Tuuta Airport and Waitangi Settlement data sets to eliminate inconsistencies prior to validating the simulation implementation. Specifically, the Waitangi Settlement data set was punctuated by missing data periods and erroneous data readings. Furthermore, the two data sets needed to be matched so that only data a) flowing at the same time and b) flowing in the same direction were considered. This process reduced two data sets of approximately 30,000 points down to a set of 650 correlated velocities for wind flowing from Tuuta Airport to Waitangi Settlement and another data set of 1500 correlated velocities for wind flowing in the reverse direction. These points are plotted in blue in Figure 4 below.

Validation Simulations

Simulations were carried out for the 45 characteristic inflow profiles for both validation directions following the methodology described above. The island cross-section for wind flow from

Tuuta Airport to Waitangi Settlement was on a bearing of 26.5°. The second validation direction was along a bearing of 206.5°. Note that in this second direction the wind must flow over particularly complex terrain prior to reaching either measuring location.

The simulated velocities 2m above the ground were exported at the Tuuta Airport and Waitangi Settlement measurement locations. These have been plotted in orange in Figure 4 below.

Validation Results

Plot (a) of Figure 4 shows a comparison of the correlated historical wind velocity data (blue) with the simulated wind velocities (orange) for the wind flow between Tuuta Airport and Waitangi Settlement (26.5°). This indicates that there is a relatively good agreement between the simulation results of the 26.5° verification direction and the verification data. Note that the least squares fitted lines only differ significantly near the origin. This is because the oceanic wind flow is the sole source of wind in the CFD model. This assumption means that if there is no inflow wind then there will be no wind at either Tuuta Airport or Waitangi Town. In reality, this is not the case.

Plot (b) shows the equivalent for the reverse direction (206.5°). This indicates that, in this direction, the CFX simulations consistently underestimate the wind flow velocity when compared to the least squares line fitted to the recorded data. This is likely to be due to the two-dimensional model failing to capture the complex nature of the three-dimensional wind flow induced by the cross-section’s complex terrain. These simulations also indicated that the two-dimensional model failed to return the atmospheric boundary layer back to its open sea state after flowing over the island as would occur in a real atmospheric boundary layer. This is show clearly in Figure 3 by the high portion of green (slower wind velocities) following the island.

This is not an unexpected result given that the two-dimensional approximation lacks the physics to fully capture the three-dimensional evolution of a real atmospheric boundary layer [6]. The validation simulations revealed that the accuracy of the simulated boundary layer is heavily dependent on level of terrain complexity upwind of the point of measurement. These inaccuracies were deemed to be acceptable in order to be able to generate estimates of wind flow for the full set of wind speeds and directions.

Turbine Power Production Methodology

A statistical methodology utilising the historical wind data and numerical simulations was developed to estimate the probability distribution of the wind flow at the turbines hub for each wind direction. This methodology required two assumptions about the nature of the wind flow on Chatham Island. These were: oceanic wind flow was uniform; and that it was the sole source of air flow on the island. These assumptions are justified by the fact that the size of Chatham Island is much smaller than the length scale of synoptic ocean wind flow hitting the island. Note that the explanation provided below is for one wind direction. This methodology was used to estimate turbine hub velocity distributions for all 16 wind directions.

The 10 years of wind velocity data from Tuuta Airport was sorted into 16 groups based on the direction of the wind flow. A unique cumulative distribution function (CDF) for the wind velocities at Tuuta Airport was created from this data for each of these 16 wind directions. This provided an estimate of the probability that any specific wind flow would occur.

The assumptions stated above mean that for each wind speed recorded at Tuuta Airport there is a corresponding oceanic wind speed which has caused the wind flow experienced at the airport. This oceanic wind velocity can be determined by running simulations in the wind direction with different inflow boundary conditions until the Tuuta Airport data is reproduced. The probability of an inlet boundary velocity occurring is then the same as the probability that the Tuuta Airport wind speed which it causes. Therefore the probability of an oceanic inflow occurring can be inferred by matching the wind velocity simulated at Tuuta Airport with the observed wind velocity data. This process was repeated for the 45 different inflow conditions to estimate the distribution of the far field wind flow. The assumption that the far field oceanic flow is uniform across the island means that the velocity distribution of inflowing wind will be the same for both the airport location and the location of the turbines. This allows simulations centred on the wind turbines to be used to map the far field oceanic distribution to the velocities simulated at the turbine hub (55m) and estimate their cumulative distribution.

Plot (a) of Figure 5 shows this process for south-westerly wind flow. The known cumulative probability distribution of the airport (—) is sampled at the simulated airport wind velocities (○). These probability values are mapped to the inflow reference velocities (○) which then are interpolated to estimate the cumulative distribution of the oceanic wind flow (—). The probabilities of each inflow (○) are then mapped to the simulated turbine velocities (○) which in turn are interpolated to generate the cumulative distribution of the turbine hub velocities (—).The CDFs were discretised in 1m/s intervals to estimate the probability of wind speeds ranging from 0m/s to 35m/s. These have been plotted as histograms to provide a more intuitive representation of the three wind velocity distributions. These are shown in plot 5b. Using the CDFs in the previous steps ensured these discretized probability values remained valid throughout the mapping process.

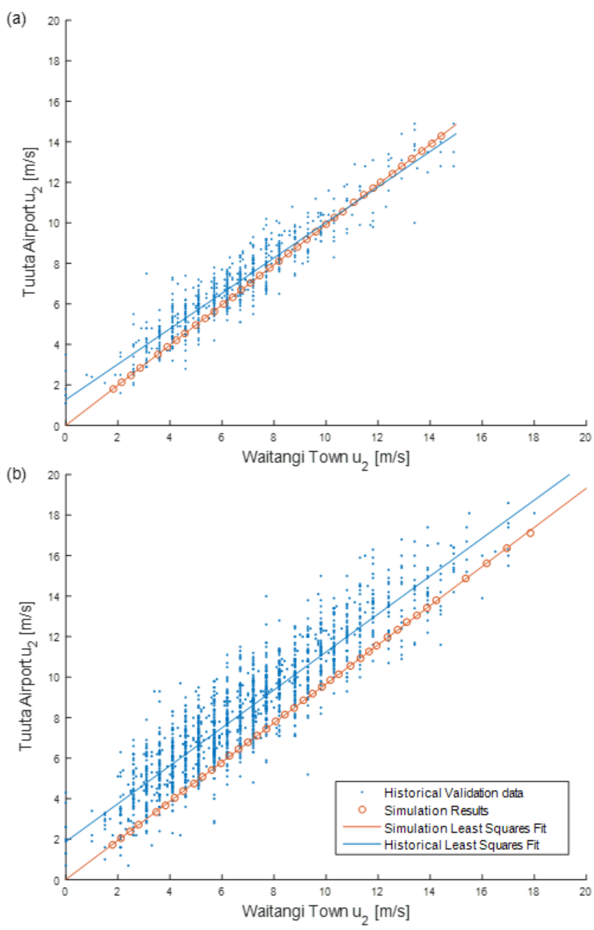

Figure 4. Model Validation for a) 26.5° from Tuuta Airport to Waitangi Settlement and b) 206.5° from Waitangi Settlement to Tuuta Airport

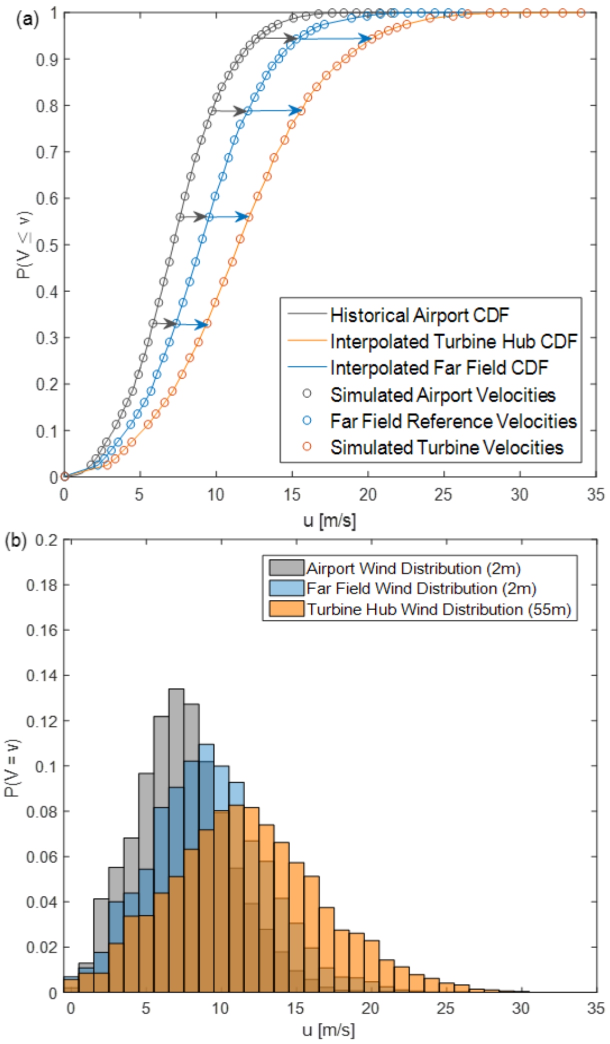

Figure 5. Comparison of a) cumulative distribution functions and b) probability mass functions

The probability distributions shown in plot 5b reflect what is expected in real world wind flow. The wind is travelling quickly over the ocean (blue) and then slows as it flows over the island causing the probability distribution (grey) to compress once it reaches the Tuuta Airport. The oceanic wind is also slowed by the island before reaching the turbines. However, as the velocity measured at the turbine hub is higher above the ground there are faster wind speeds in the distribution which are less affected by the island. This leads to a "faster" turbine hub velocity distribution (orange) that is more stretched in nature.

Equation (1) was used to calculate P_k, the expected power production for each wind direction.

$$P_k = \sum_i f(v_{ik})\, p_{ik} \tag{1}$$

Here, indices k and i represent the wind direction and inflow profile respectively. v_{ik} represents the velocity at the turbine hub for inflow profile i in direction k, p_{ik} represents the probability of this velocity occurring and $f(x)$ is the turbine's power production at the wind velocity x. The total expected power output (P) was calculated using the following equation.

$$P = \sum_k P_k\, p_k \tag{2}$$

Here p_k is the probability of the wind being in direction k and P_k is the directional power production calculated from Equation (1).

Turbine Power Production Estimate

The statistical methodology described above estimated the power output of a single Chatham Island turbine to be 125kW. Comparisons with the data provided by CIEL indicated that, in reality, the power output of the turbine was far less than the above estimate. Discussions with CIEL's chief electrical engineer revealed that when operational considerations are considered the results presented here are consistent with what has been recorded.

Conclusions

The work presented in this report focused on developing a generalised CFD framework capable of modelling wind flow over complex terrain. Chatham Island was used as a case study in this development which allowed the CFD framework's accuracy to be assessed through comparisons with historical climate data and power generation records. This validation indicated that the two-dimensional simulations failed to fully capture the three dimensional complexities of true atmospheric wind flow. This was not an unexpected result. However, the two-dimensional simulation results were accurate enough to use in a framework capable of simulating the full range of wind conditions in a computationally efficient manner. When used to estimate the power production of the turbines, the CFD framework produced values significantly larger than the turbine power measured output. However, after adjustment for the effect of operational losses, the simulated values are a close match to the CIEL data.

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