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# WIND PROFILES OVER COMPLEX TERRAIN

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## Abstract

Over an area with a complex topography the neutral wind profile is more difficult to predict then it is over flat terrain. Theoretical approaches have been given for relatively simple situations (such as an isolated hill or a ground plane with parallel ridges) and verified by measurements. As it does over flat land, atmospheric stability also influences the wind profile over complex terrain. As a consequence the ratio between higher (hub height) and lower (near ground) altitude winds depends on topography and atmospheric stability. Some general insights into this topic will be given and results of some measurements.

## Introduction

At the first Wind Turbine Noise conference in Berlin, in 2005, several papers showed that the commonly used logarithmic formula does not correctly describe the wind profile in an atmosphere in a non-neutral state. In an unstable atmosphere this leads to an overestimate of the higher altitude wind speed, in a stable to an underestimate. From a noise perspective, the latter situation is more important as the discrepancy between a stable and neutral atmosphere is greater and has more effect on the noise output. Also, in the temperate climate zone the stable atmosphere is a common phenomenon after sundown, so this coincides with the time of day that noise levels usually must be lower. A stable atmosphere is thus the critical condition.
As a result of this shortcoming the relation between background sound (related to near ground wind) and turbine sound (related to higher altitude wind) often has not been determined properly as it was based on a 10 m altitude wind speed and a forever logartihmic wind profile. However, over flat land it is possible to give a correct description of the wind profile using the Monin-Obukhov similarity theory leading to a

stability correction added to the logarithmic profile. Holtslag [1984] gives a procedure to calculate the wind profile using near ground weather observations.

Over complex terrain the relation between wind speeds and wind directions at different altitudes is influenced also by the changes in ground height and as a result the situation is much more complex. Botha [2005] proposed to do away with the 10 m wind speed as the usual starting point to predict wind turbine noise levels and to relate all sound levels (from wind turbine and background) to the wind speed at rotor height. This proposal is superior to the practice of using only 10 m wind speeds in an apparently forever neutral atmosphere. Unfortunately it gives no insight into what actually happens below the rotor. To understand the impact of wind turbine noise it is important to understand, at least qualitatively, the behavour of the wind. This is demonstrated by Botha himself who concluded that in two of the cases he considered the atmosphere was predominantly neutral: this did seem to be the case at the location of the measurement on a mountain top, but it was not true in the valley below where the residents live.

This paper gives an overview of research results but represents only part of the knowledge available in this topic –*viz.* as far as it concerns the application to wind energy. It is limited to the changes in average wind speed due to topography and atmospheric stability and does not deal with turbulence, although this is an important feature of wind in complex terrain that has to be considered to be able to predict effects on wind turbines. To the author's knowledge as yet no information on wind in complex terrain is available that is directly applicable to the topic of wind turbine noise.

## Flow over ridges in a neutral atmosphere

When a ridge is perpendicar to the main wind flow, the near ground air is forced upward. This air will not be compressed by the upward forcing when the slope is gentle which is the case when the dimensionless number NH/U is small. Here H is the maximum obstacle height, U is the average undisturbed wind speed, and N is the buoyancy frequency $N = \sqrt{(-g/\rho \cdot d\rho/dz)}$ [Baines 1995] where g is the graviational acceleration, $\rho$ is air density and z is height. N is the frequency of free vertical, buoyancy driven oscillations of small amplitude and has a maximum value of approximately 0.01 rad/s which is approximately the inverse of 15 seconds. When a forced vertical movement is fast relative to N the air cannot follow this change and will be compressed.

As the air flows uphill the lower air is accelerated whereas at high altitude the wind speed will not (yet) be affected. In figure 1 results from Beljaars *et al* [1987] are shown from the relatively 'smooth' (roughness height 3 cm) isolated Askervein hill on South Uist, Scotland, that is elongated in the direction perpendicular to the wind at the time of measurement. The top of the hill is 120 m above the surrounding terrain, 400 m from the upstream foot of the hill and very nearly symmetrical; in the cross

direction the hill has a length of almost 2 km. The vertical parameter in figure 1 is the speed-up ratio $\Delta s = (V_{10}/V_{10,upstream} - 1)$where $V_{10,upstream}$ is the (topographically) undisturbed wind speed at 10 m height. The figure shows the results of three different models with actual measurements at 10 m height above (local) ground for a neutral atmosphere. It shows that the wind blows strongest at the top whereas it is

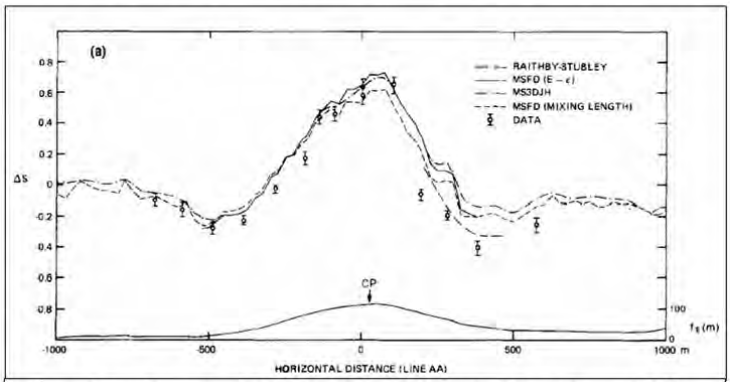


Figure 1: speed-up ratio, the change in 10 m wind speed relative to the upwind 10 m wind speed, plotted vs. distance in the streamwise direction from the top of Askervein Hill [figure from Beljaars *et al* 1986]

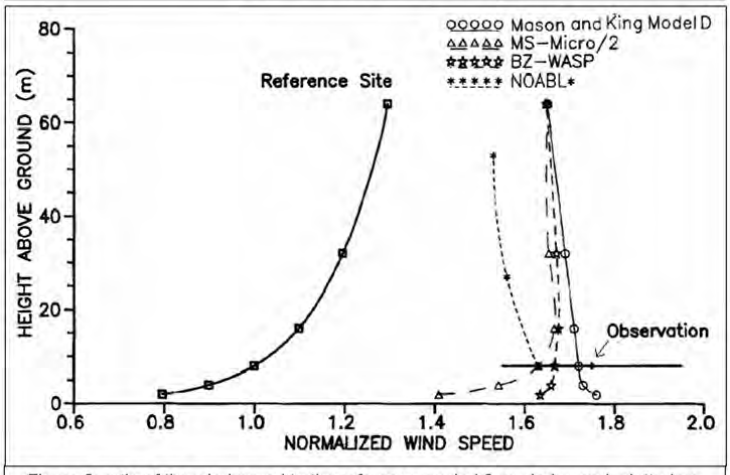


Figure 2: ratio of the wind speed to the reference upwind 8 m wind speed, plotted vs. height above local ground, in the (undisturbed) upwind reference point (left) and over the top of Blashaval Hill [figure from Walmsley *et al* 1990]

relatively calm at the foot of the hill due to a decrease of wind speed. Although the speed-up ratio at the top of the hill (almost 0.8, *i.e.* $V_{10}/V_{10,upstream} \approx 1.8$) refers to the up-stream 10 m wind speed, it is also a speed-up relative to a point at the same height without the hill. Over flat land, the wind speed ratio in a neutral atmosphere over 3 cm roughness would be $V_{120}/V_{10} = 1.43$. Thus, the hill creates an increase in wind speed at its top relative to that same altitude without the hill.

Walmsley *et al* [1990] obtained similar results for Blashaval Hill, Scotland. This hill has dimensions and roughness comparable to Askervein Hill. In figure 2 modelling results are plotted showing the wind speed above an upwind reference point undisturbed by topography, and above the 100 m high top of the hill, relative to the reference point wind speed at 8 m height. It shows that at the hill top the near ground velocity shear is strongly reduced compared to the near ground wind over flat land at the reference point. In fact at the hill top there is an increase close to the ground according to two models and a slight *de*crease in wind speed above ≈10 m according to all models. Beljaars *et al* [1986] give more detailed modelling results for the wind speed perturbation over periodic, sinusoidal ridges with a wave length (top to top or valley to valley) $\lambda$. In figure 3 results are plotted for three models (the MS3DJH model is the same as the MS-Micro/2 model used by Walmsley *et al*). On the abscissa is the dimensionless parameter $(z + z_o)/\lambda$, where z is height above ground and $z_o$ is the roughness height. Three situations are given for (from left to right in figure 3) relatively longer or relavitely smoother hills, with values for $\lambda/z_o$ of $10^3$, $10^5$ and $10^7$, respectively. At $\lambda/z_o$ =

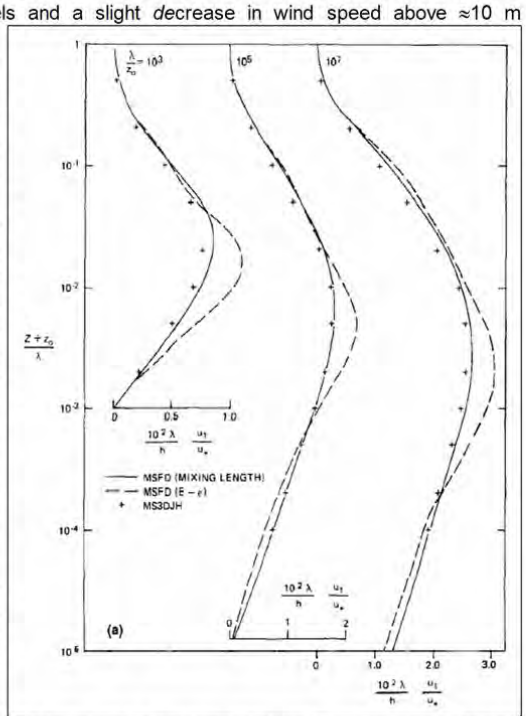


Figure 3: wind speed perturbation at dimensionless 'height' $(z+z_o)/\lambda$ over the top of a (periodic) ridge relative to the wind speed at the same height over flat land [figure from Beljaars

$10^5$ the maximum perturbation (relative to the profile at the same height above flat ground) in wind speed is at a height of $z \approx 0.005 \cdot \lambda - z_o$, which for an inter-ridge distance up to 1 km is less than 5 m. The perturbation vanishes at a height of appr. ½ $\lambda$.

When changes in ground height are small, the relief can be treated as increased rougness. Then, in a neutral atmosphere, the wind speed can be determined from the logarithmic wind profile, given a reference wind speed and the roughness and displacement height (defining a plane below which the model is not valid):

$$V_z \cdot \log[(z - d)/z_o] = V_{ref} \cdot \log[(z_{ref} - d)/z_o] \qquad (1)$$

Kustas *et al* [1986] applied this approach to a hilly region in the Swiss Voralpen ('Pre-alps') described as (non-periodic) statistically uniform terrain with hills of approximately 100 m height and distances between major peaks of about 1 km. They showed that in neutral conditions eq. 1 could be used to describe the wind speed and inferred that on average $z_o = 3.8 \pm 1.3$ m and d = 45 m. The displacement height is thus about half the (major) peak height; this approach can therefore not be used to describe the wind in the valleys.

## Flow in valleys in a neutral atmosphere

We now take a closer look at the flow in the valleys between the ridges. From figure 1 it was apparent that for a single ridge the wind speed at the foot of the hill, upwind as well as downwind, is lower than it would be without the hill.

Baines [1995] gives an overview of modelling results for valleys modelled as single and periodic depressions. For a single depression and hydrostatic equilibrium (corresponding to a neutral atmosphere) the wind flows through the valley, but above a critical value of NH/U (where H is now the depth of the depression), the air at the bottom of the valley becomes stagnant. For an increasing value of NH/U the thickness of the stagnant layer increases. The critical value for a radially symmetric depression of the form $z_{ground} = -H/(1+(r/a)^2)$ is 0.85; for asymmetrical forms it is between 0.5 and 1. This means that for $U/H < N/0.85 \approx 0.012$ there will be still air at the bottom of the valley. A vortex will develop in the valley above the upwind slope of the valley if the slope is steep enough. This occurs when $NL/U < \pi$ where L is width of the downslope side of the valley; if (in a symmetrical valley 2L wide) $NLU < ½\pi$, the vortex formed at the downslope will dominate most or all of the valley [Baines 1995].

In periodic valleys, between periodic ridges perpendicular to the wind, the behaviour of the wind is essentially a repetition of the single valley, air being swept from one valley into the other [Baines 1995], though each valley may have still air at its bottom when NH/U exceeds the critical value. The influence of a hill in the upwind direction is negligible, but increases when the atmosphere becomes more stable [Hunt *et al* 1984]. In the downwind direction the wake can influence the flow around a nearby

hill, though for relatively low and smooth hills the flow of one hill can be superimposed on the next to determine the total flow [Hunt *et al* 1984].

When the wiond has a compionent in the direction of the valley, the wind below the ridges will be forced by topography to follow the valley, the more so if the valley is deep. Enger *et al* [1993] give a clear example of this from a north-south running section of the Colorado River Valley, USA, where the wind direction below the ridges that are 1 to 2 km above the valley floor, is either north or south, irrespective of the east-west component of the geostrophic wind.

### Flow over ridges in a stable atmosphere

In the temperate climate zone an inversion usually develops at sundown that becomes more pronounced in the course of time. After sunrise it may remain present, but especially at high insolation it will disappear due to turbulent mixing. Above the inversion an adiabatic temperature gradient can be assumed, below it this gradient is inverted and temperature increases with height. This implies that above the inversion the atmosphere is neutral. Usually inversions have a height of up to several hectometers. Thus the situation at sufficiently high hill tops, which are closer to or perhaps above the inversion height, will be more similar to the neutral atmospheric state than the situation in the valleys is. A very broad hill top can be viewed as a plateau where the wind profile will adapt to the new, higher ground level; after a long fetch at the new height this will develop into a stable wind profile, irrespective of ground height.

### Flow in valleys in a stable atmosphere

In a stable atmosphere the near ground air is relatively cool and heavy. With no wind this cool air will therefore flow towards the lowest point and the lower part of the

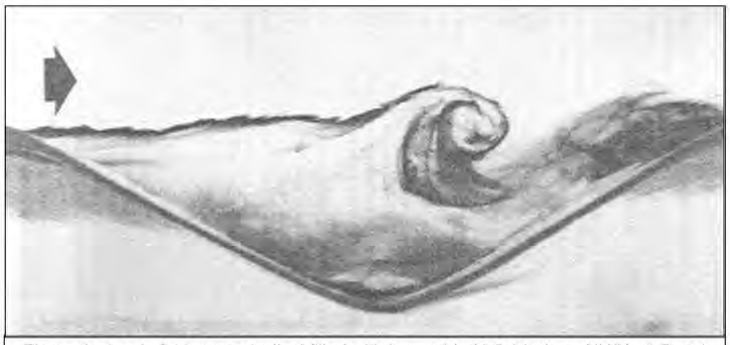

Figure 4: steady flow over a 'valley' filled with heavy (dark) fluid where NH/U =1.5 and H/L = 0.45; dye marks the separation between the flow over and in the valley. At the downwind side there is turbulent mixing (figure from [Baines 1995]).

valley will be filled with cool air. When there is some wind at higher altitudes, there will be a mixing layer between the stagnant valley air and the moving air above it. Figure 4, taken from Baines [1995], gives a laboratory example of steady flow over a depression filled with heavy fluid. Here the flow is strong enough to push some fluid from the upslope out of the valley. To push the heavy fluid entirely out of the valley the criterion NL/U << 0.5 must be met, where L is the half-width of the valley. When NL/U >> 0.5, the fluid will stay in the valley and not move. In between these values some heavy fluid will leave the valley and the remaining fluid will accumulate on the downwind slope (the dark patch at the right in figure 4). Enger *et al* [1993] illustrate this for the practical case of the Colorado River Canyon, showing a vortex on the downwind side of the canyon with wind speeds in excess of the geostrophic wind (7 m/s) and almost still air at the upwind slope.

Periodic ridges with a cross flow can be regarded as a repetition of single valleys, except that if cool air is pushed out of one valley it will enter the next [Baines 1995]. In a stable atmosphere cool air is in fact produced in the valleys, so the net loss of cool air in a valley is less than in a single valley and valleys further downwind will contain more cool air. In figure 5 this flow is plotted for three values of NH/U when the flow already has traversed several valleys and can be considered nearly steady. In figure 5 instantaneous streamlines as plotted as solid lines (dotted lines are potential density); in all three cases there is stagnant air in the valley. From the values of NH/U (with N = 0.01 rad/s and H = 500 m) one can conclude that the geostrophic wind speed is (from top to bottom) 7, 4 and 2 m/s, respectively. Fromn figure 5 one can conclude that when the geostrophic wind speed increases the height of the stagnant air pool in the valley decreases.

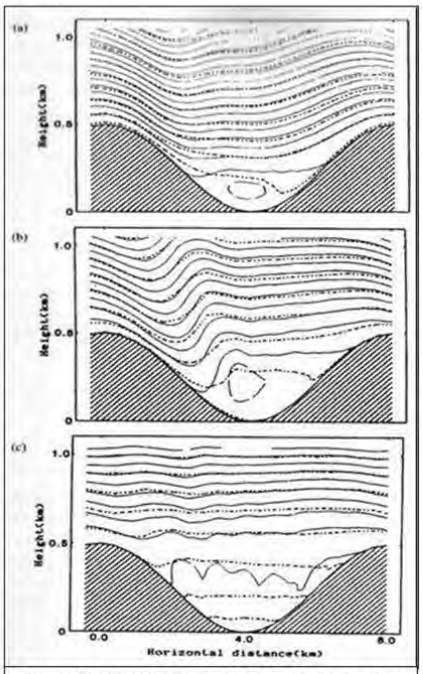


Figure 5: streamlines in the flow across a valley (solid lines) and contours of potential density (dotted lines) where NH/U has a value of 0.69 (a), 1.38 (b) and 2.44 (c) (figure from [Baines 1995], originally from [Kimura *et al* 1988])

In figure 6 a fine example of stable (evening) atmospheric conditions is shown on a popular leaflet of the Sydney CityRail. In the valley cool air is visible as fog as a result of condensation due to ground cooling. Also, on the plateau a thin layer of fog has formed.

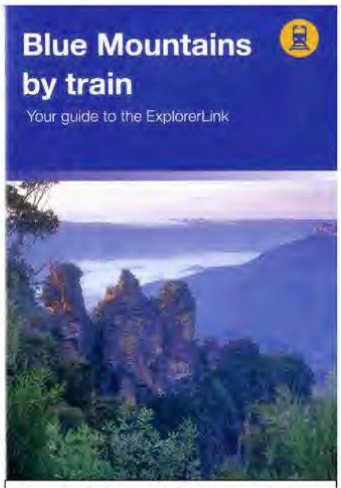

Figure 6: fog revealing the presence of stable air on a Sydney CityRail brochure

### Downslope wind in a stable atmosphere

On a sloping surface the cooling of near ground air will cause it to flow downward. Thus the air on valley slopes will flow downward and fill the valley bottom. Brost *et al* [1978] have investigated this for a single sloping plane, and show how the thickness of the stable boundary layer depends on the direction of the wind relative to the slope. Although the authors conclude that the effect of slope on the flow is strong, these calculations were done for a slope of 0.002 which is lower than one would expect in hilly terrain. When the wind flows upslope the most stable layer develops; the flow reverses in direction when ascending from the ground up to a height where the prevailing wind blows. This was also found for the much steeper Colorado River Canyon, where the vortex developed on the downwind slope.

### Case 1: wind measurements near Makara, NZ

For a projected wind farm close to the village of Makara, New Zealand, data were collected to be able to correlate the wind speed in a valley with the wind speed on top of ridges. Makara is a village in a valley running from SSW to NNE between approximately parrallel ridges up to 400 m above the valley floor. The wind farm is projected on the ridge west of the valley (and further away). Northern to northwesterly winds are predominant in the area, otherwise southern winds prevail; winds from other directions are rare.

The wind data presented here are from an anemometer mounted at 122 m height on a mast on Mount Kaukau, 10 km NE of Makara, on a location at 425 m above MSL, and were provided by the New Zealand Met Office (data fro. This anemometer is thus somewhat higher than the planned wind turbine rotors will be. Valley wind speeds (the 'Makara valley data') are from a 4 m high anemometer on a location appr. 80 m above MSL at 60 South Makara Road, and were provided by an amateur meteorologist. The anemometer is out in the open and not sheltered by any trees or

buildings. The data presented here are from hourly values in the period October 19, 2004 through December 31, 2005.

First in figure 7 results are shown from measurements over the year 2005 at Wellington airport, with a relatively flat and low surface, 10 km ESE of Makara. The anemometer is at 10 m above MSL. Figure 7 shows the averages per clock hour over all hours when the wind was northerly (which is the case for most of the time), over the four seasons. The fact that the wind picks up in the morning and abates in the evening is a direct result of a stable atmosphere (with low surface wind speed) that becomes unstable after sunrise (when surface wind increases). With southerly winds, when the air has moved over a long fetch of water where the differences between day and night time surface temperature are much smaller than on land, the difference between day and night wind speed is also smaller. From figure 7 it can be concluded that nighttime atmospheric stability is a common phenomenon in the area.

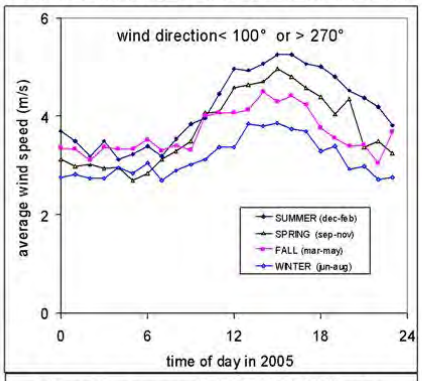


Figure 7: average wind speed at Wellington airport for ofshore winds (direction between West and East over North); averages per clock hour over all hours in 2005

In figure 8 the average wind speeds are plotted per season in the Makara valley and on top of Mount Kaukau. For the valley data the figure clearly shows the diurnal pattern of low near surface nighttime wind speed (stable atmosphere), increasing after sunrise (change to unstable atmosphere), and the reverse process around sunset. Also, as expected, the differences are greater in spring and summer because of increased heating of

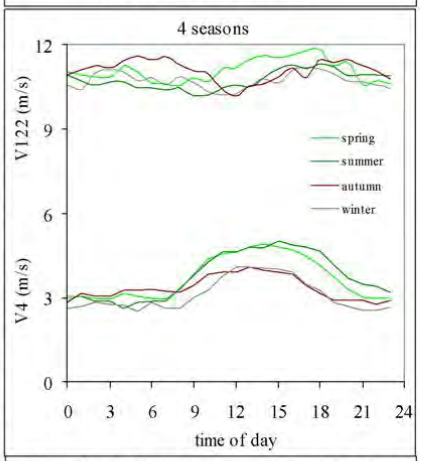


Figure 8: wind speed averaged per clock hour over Mount Kaukau (V122) and in Makara Valley (V4) over the seasons in period Oct.

the surface in daytime. In fact the results are very much similar to those of Wellington airport (figure 7).
For the mount Kaukau data the pattern is reversed, as is expected for higher altitudes: here the wind abates, though only lightly on average, in the morning and picks up again at night.

The wind farm developer has measured wind speeds at 40 m and 80 m altitude above the top (299 m) of Quartz Hill, 5 km north of Makara (these data were not made available). The wind shear, determined from wind speeds at 40 and 80 m height above Quartz Hill, is low: V80 is, on average, 5% higher than V40. Data from two heights at Mt. Kaukau (26 m and 122 m AGL) yield approximately the same results: on average the wind speed in daytime at 122 m is some 10% higher than at 26 m (at night this is 20%). This low wind shear is the combination of the higher altitude near-neutral atmosphere and the effect of acceleration of the wind when it ascends the slope.

In figure 9 the average ratio of the 122-m wind speed at Mt. Kaukau and the 4-m wind speed at South Makara Road is plotted for summer and winter. Also plotted are the ratio's that were exceeded for 10% and 90% of the time, respectively, showing values can significantly deviate from the average ratio for a considerable part of the time. In fact the valley wind speed was below 2 m/s for 31% of the total time (night and day), whereas such a low wind speed over the hill top is rare (2% of the time). The 31% corresponds to 60 to 70% (depending on season) of the hours between sunset and sunrise.

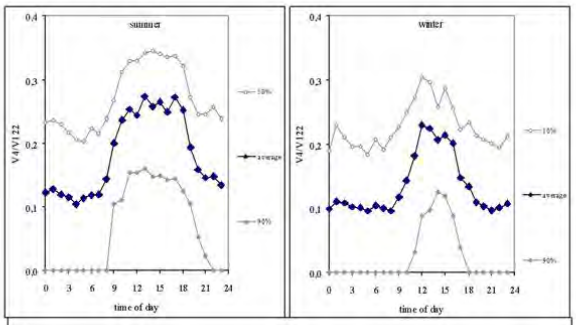


Figure 9: average ratio of the wind speed in Makara valley and over Mt. Kaukau and ratio's exceeded for 10% and 90% of the time in summer and winter; values per clock hour in period Oct. 2004

The results in figure 9 show that at night the wind speed in the valley is on average 20 to 25% of the hill top wind speed in daytime, but this decreases to appr. 10% at night time. These are averages: at night it is very common that the wind speed is

zero or very weak (< 2 m/s). These values may be somewhat different when taking different locations, but the differences will be small as they only depend on small deviations from the general situation (the ridges vs. the valley floor). If this were not the case, then measurements from one location (such as Mt. Kaukau or Quartz Hill) would not represent the conditions in a larger area.

### Case 2: observations in Taralga, NSW

Taralga is in an area with rolling hills and height variations up to several hundreds of meters, in New South Wales, Australia. A wind farm developer proposed to erect wind turbines on high places in the area. To determine the wind resource, several measurement masts have collected wind speed data. As was the case in NZ (above) these data were not made public, though in this case they could be analysed by the other parties. From the measurements the developer concluded that there was no significant wind shear. At one of the masts wind speeds were measured at 20, 35 and 50 m height. Our analysis of the wind shear between 35 and 50 m (calculated from the 35 and 50 m wind speeds, for 50-m wind speeds higher than the cut-in wind speed of the turbines), showed that 31% of all shear exponents were negative, which means that the wind speed decreases with height above 35 m. At the same time there was usually an increase in wind speed between 20 m and 35 m height.
In fact, the correlation between both sets of wind shear exponents was relatively low; the wind shear below 35 m determined 34% of the wind shear above 35 m, for the rest other factors are apparently important (correlation coefficient is 0.59 → variation is 0.34). Between 6PM and 7AM the proportion of time with a negative shear above 35 m was lower (15%), and there was less correlation between wind shear above and below 35 m (correlation coefficient is 0.53 → variation is 0.28).
The fact that there is often a change in wind shear somewhere between 20 m and 50 m over the hill can be understood from the flow over a hill as shown in the sections above, and demonstrates that the wind profile from ground level to projected hub height cannot be described correctly by the logarithmic wind shear formula that is valid over flat terrain. Taking simple averages of the wind shear between 20 and 50 m obscured the fact that for a significant proportion of time there is no steady increase of wind speed with height, but a maximum somewhere between 20 and 50 m height over the hill top. From these data it is not possible to determine the wind speed in the lower parts of the area.

Mr. Ross, a resident of this very quiet area, made interesting observations at his house that stands in a low part of the area with no direct neighbours and surrounded by hills on which the turbines were planned. He kept a diary of his weather observations of which a period of 87 days in April to July 2006 (the southern autumn and winter) will be shown here. Interestingly, a closeby wooded ridge, approximately 70 m higher than the house, provided an indication of the higher altitude wind speed: when it was very calm at his house he could often hear the rustling of the trees on the high part of the hill, and he could see (when it was light) the movement of the

leaved branches above a certain altitude. This was only seen at 'night time' (in a broad sense: with the sun low or down). In fact nature here demonstrates that a resident can experience no wind in the valley while at the same a wind turbine at the top would experience a high wind speed.
In figure 10 mr. Ross' observations are summed up graphically: out of 86 days of observations (he was out one day) in 34 nights he observed rustling on the ridge, in various degrees of loudness, while at his house it was calm. These days are not scattered randomly but are more or less grouped according to the passage of weather systems that have a succession time of several days to a week. Also, in many of these days he observed fog in the low parts; in fact this is a visualization of the cool near ground air. He also observed more than a light clouding in seven occasions, which never coincided in time with the high wind shear.

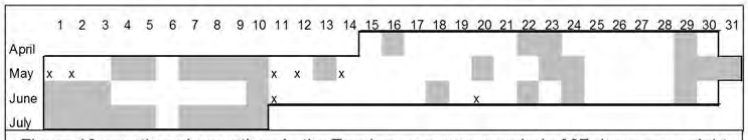


Figure 10: weather observations in the Taralga area over a period of 87 days; grey: night with no or very little wind at house, wind on high ridge; x: sky (partly) clouded; white: other conditions

## Conclusion

Atmospheric stability and topographic forcing are important determinants of the wind profile in complex terrain. Due to topographical height variations the near ground wind can be slower or faster than the higher altitude wind. Over a hill the wind speed will usually be higher than it would be at that point in space without the hill. At the same time the wind speed in the valley will usually be lower than it would be without the hill. Topography can enhance or decrease the effect that atmospheric stability has on near ground wind. In general, at night a valley will be calm while the wind will keep on blowing at high tops.
From measurements on high places in complex terrain it is not possible to calculate the wind speed in lower parts; the commonly used logarithmic (neutral) wind profile cannot be used in complex terrain, even less so when the atmosphere is stable.

From an energy perspective the high places in complex terrain are therefore most attractive, though added turbulence and wind shear due to topographic forcing may increase the dynamical load on a turbine.
From a noise perspective this means that in valleys it can be very quiet, especially at night, while on hill tops the wind may drive wind turbines at high speed. Thus, the perception of wind farms by residents in hilly terrain is not very different from residents in flat terrain where atmospheric stability produces the same effect. An advantage of hilly terrain may be that it can help in shielding wind turbines aurally and visually, though this depends on position as it can also enhance perception.

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